# DWI of the Spinal Cord with Reduced FOV Single-Shot EPI

Drew Mitchell

MD Anderson Cancer Center

June 17, 2015

Magnetic Resonance in Medicine 60:468–473 (2008)

# DWI of the Spinal Cord with Reduced FOV Single-Shot EPI

Emine Ulku Saritas,[1*] Charles H. Cunningham,[2] Jin Hyung Lee,[1] Eric T. Han,[3] and Dwight G. Nishimura[1]

**Single-shot echo-planar imaging (ss-EPI) has not been used widely for diffusion-weighted imaging (DWI) of the spinal cord, because of the magnetic field inhomogeneities around the spine, the small cross-sectional size of the spinal cord, and the increased motion in that area due to breathing, swallowing, and cerebrospinal fluid (CSF) pulsation. These result in artifacts with the usually long readout duration of the ss-EPI method. Reduced field-of-view (FOV) methods decrease the required readout duration for ss-EPI, thereby enabling its practical application to imaging of the spine. In this work, a reduced FOV single-shot diffusion-weighted echo-planar imaging (ss-DWEPI) method is proposed, in which a 2D spatially selective echo-planar RF excitation pulse and a 180° refocusing pulse reduce the FOV in the phase-encode (PE) direction, while suppressing the signal from fat simultaneously. With this method, multi slice images with higher in-plane resolutions (0.94 × 0.94 mm$^2$ for sagittal and 0.62×0.62 mm$^2$ for axial images) are achieved at 1.5 T, without the need for a longer readout. Magn Reson Med 60:468–473, 2008.**


**Key words: diffusion weighted imaging; spinal cord; reduced FOV; EPI**

ing magnetic field gradients ($G_{\mathrm{Diff}}$) (4). These phase errors differ for each repetition time (TR), manifesting themselves as ghosting artifacts in the multi shot diffusion-weighted (DW) image, and an overestimation of the apparent diffusion coefficient (ADC). All of these factors add up, yielding very low-signal, low-resolution DW images for the spinal cord with artifacts.

The most frequently used technique for DWI, especially for the brain, remains ss-EPI (5). Because the ss-EPI sequence acquires the whole of $k$-space after a single excitation pulse, the magnitude images do not suffer from the ghosting artifacts arising from motion-induced phase errors. The drawbacks of the ss-EPI method are the long readout that experiences $T_2^*$ decay, causing severe blurring of the images along the PE direction, and the long interval between subsequent $k$-space profiles that result in significant phase errors due to off-resonance (e.g., from chemical shift, $B_0$-inhomogeneities, susceptibility gradients, eddy currents). Furthermore, the water–fat chemical shift artifact in ss-EPI, which can be quite substantial, needs to be avoided by using either fat suppression or spectrally selec-

# Table of Contents

# Introduction

- Spinal cord diffusion-weighted imaging (DWI) can diagnose disorders from fiber tract damage
- Several challenges:
  - Magnetic field inhomogeneities around spine create off-resonance artifacts
  - Partial volume effects from CSF and lipid
  - Spinal cord cross section very small
  - Bulk physiologic motion from heart, breathing, swallowing, CSF pulsation
- Phase errors differ for each TR, make ghosting artifacts for multi shot DWI, and overestimate apparent diffusion coefficient (ADC)
- Result is low-signal, low-resolution DW images with artifacts in spinal cord

# Introduction

- Single-shot echo planar imaging (ss-EPI) most frequently used technique for DWI
- Advantages:
    - Acquires whole k-space after single excitation pulse
    - No ghosting artifacts from motion-induced phase errors
- Drawbacks:
    - Long readout experiences $T_2^*$ decay, blurring images in PE direction
    - Long interval between k-space profiles result in phase errors from off-resonances
    - Water-fat chemical shift artifacts are severe and must be avoided by fat suppression or spectrally selective excitation
- Magnetic field inhomogeneities around the spine, plus these drawbacks, make quality ss-EPI spinal cord images difficult

# Introduction

- Spinal cord imaging benefits from reduced FOV applications (because of narrow anatomy)
- Reduced FOV methods decrease the readout duration, reduce off-resonance artifacts, and enable ss-EPI techniques
- Excited FOV in PE direction reduced by using 2D spatially selective echo-planar RF excitation pulse and $180^\circ$ refocusing RF pulse
- Required number of k-space lines in PE direction decreased by reducing FOV, which leads to higher resolution for fixed scan time
- Combination of 2D RF pulse and $180^\circ$ refocusing RF pulse allows multi slice imaging and suppresses fat signal

# Theory

In this paper, a standard DW spin-echo ss-EPI sequence is used, with excitation pulse replaced with 90° 2D spatially selective echo-planar RF pulse that reduces FOV in PE direction

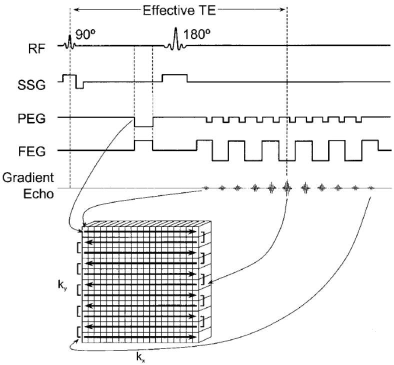



**FIGURE 15-23.** Single-shot echo planar image (EPI) acquisition sequence. Data are deposited in the k-space with an initial large PEG application to locate the initial row position, followed by phase encode gradient "blips" simultaneous with FEG oscillations to fill the k-space line by line by introducing one-row phase changes in a zigzag pattern. Image matrix sizes of 64 × 64 and 128 × 64 are common for EPI acquisitions.

# 2D Echo-Planar RF Pulse

- 2D echo-planar pulses provide control of slice thickness in two orthogonal directions independently by combining two RF pulses
- The "slow" (blipped) and the "fast" axes gradients and RF pulses are designed to achieve desired excitation profiles in each spatial direction for EPI trajectory through k-space

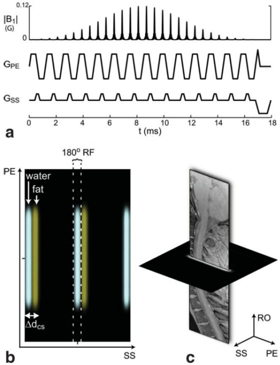



FIG. 1. (a) 2D echo-planar RF pulse and (b) simulation of the excitation profile showing how the 2D RF pulse and refocusing 180° RF pulse pair select water only in the main lobe (color coded for illustration purposes). Note that water and fat profiles are shifted by $\Delta d_{cs}$ in the SS-direction. (c) The resulting water slice and slab profile shown in 3D, along with the reduced FOV image.

# 2D Echo-Planar RF Pulse

- The two orthogonal directions are the slice-select (SS) direction and the slab-select direction (phase encode direction during imaging)
- The echo-planar RF pulse creates a 90° flip angle over 4 mm (SS direction) $\times$ 4.5 cm (PE direction) slab

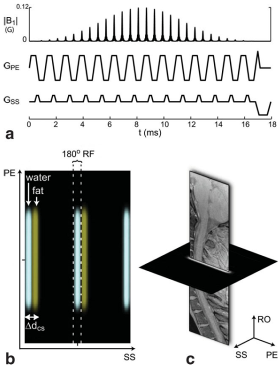



FIG. 1. (a) 2D echo-planar RF pulse and (b) simulation of the excitation profile showing how the 2D RF pulse and refocusing 180° RF pulse pair select water only in the main lobe (color coded for illustration purposes). Note that water and fat profiles are shifted by $\Delta d_{cs}$ in the SS-direction. (c) The resulting water slice and slab profile shown in 3D, along with the reduced FOV image.

# 2D Echo-Planar RF Pulse

- The pulse duration is 16.8 ms with 14 blips in the SS direction
- The excitation profiles for fat and water are displaced in volume along the blipped (SS) direction
- Excitation profile period in SS direction, because blipped gradients in SS direction fill RF excitation k-space discretely

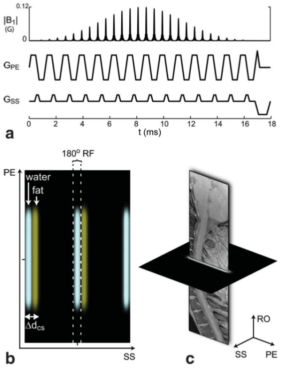



FIG. 1. (a) 2D echo-planar RF pulse and (b) simulation of the excitation profile showing how the 2D RF pulse and refocusing 180° RF pulse pair select water only in the main lobe (color coded for illustration purposes). Note that water and fat profiles are shifted by $\triangle d_{cs}$ in the SS-direction. (c) The resulting water slice and slab profile shown in 3D, along with the reduced FOV image.

# 2D Echo-Planar RF Pulse

- The spatial displacement between fat and water caused by the echo-planar path of the 2D RF excitation pulse is

$$\Delta d_{CS} = \frac{N_{blip} f_{CS} T_{fast}}{K_{blip}}$$

- The displacement $\Delta d_{CS}$ between fat and water can be designed so that the excited fat profile is entirely outside the water profile

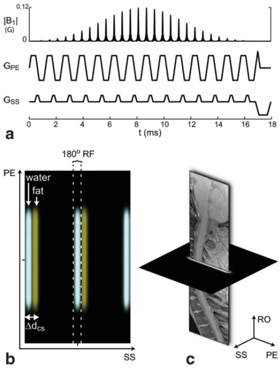



FIG. 1. (a) 2D echo-planar RF pulse and (b) simulation of the excitation profile showing how the 2D RF pulse and refocusing 180° RF pulse pair select water only in the main lobe (color coded for illustration purposes). Note that water and fat profiles are shifted by $\Delta d_{cs}$ in the SS-direction. (c) The resulting water slice and slab profile shown in 3D, along with the reduced FOV image.

# Refocusing RF Pulse

- After 2D RF excitation, a normal 180° refocusing RF pulse is used, selective in SS direction
- Crusher gradients before and after the pulse are used
- Using 2D RF excitation pulse and 180° refocusing RF pulse together suppresses signal from outside lobes of periodic 2D excitation and fat signal
- Fat suppression is particularly important in EPI, because fat signal can cause severe artifacts due to its dramatic shift in PE direction relative to water

# Multi Slice Imaging

- Multi slice imaging is not possible for FOV restriction that uses two separate 1D RF pulses, which excites adjacent slices
- 2D echo-planar RF pulses do not excite adjacent slices, making contiguous multi slice imaging possible
- Upper limit on number of simultaneously imaged slices:

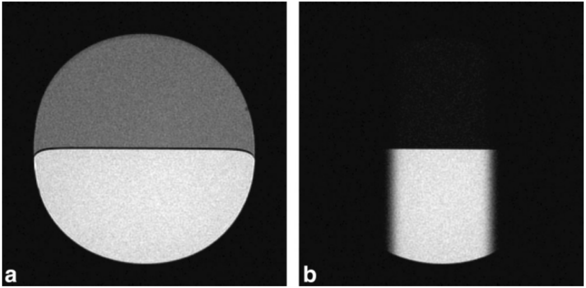
$$max\left(N_{slices}\right) = \frac{\Delta d_{replicate}}{\Delta d_{SS}} = \frac{N_{blip}}{TBW_{SS}}$$

- With three sagittal slices the whole pulse sequence takes less than 120 ms per slice, allowing multi slice imaging in one cardiac cycle

# Phantom Experiment Results

When using 2D selective RF pulse and 180° refocusing pulse pair, no outer volume excitation is observed in phantom, and fat signal is suppressed

FIG. 2. (a) Axial full-FOV image of a water/fat phantom. (b) The result of using 2D-selective RF pulse and 180° refocusing RF pulse pair to achieve a reduced FOV excitation. Note that in (b), the signal from fat on top is also suppressed. Both images were acquired using a 2DFT spin-echo sequence with 12 × 12 $cm^2$ FOV, with the only difference being the RF excitation pulse.



# In Vivo Imaging Results

- Reduced FOV ss-EPI provides two times higher resolution for same readout time compared to full-FOV ss-EPI
- The trade-off is lower SNR due to four times smaller voxel size

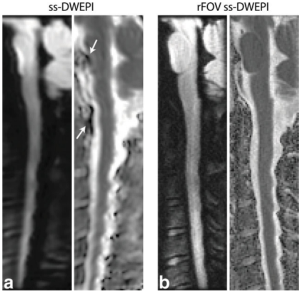



FIG. 3. Comparison results for (a) full-FOV ($18 \times 18$ cm$^2$) ss-DWEPI (only the $18 \times 4.5$ cm$^2$ region around the spine is displayed) and (b) higher resolution reduced FOV ($18 \times 4.5$ cm$^2$) ss-DWEPI. Shown are isotropic DW images ($DW_{iso}$) and corresponding $ADC_{iso}$ maps, from left to right. Both methods have the same readout time for comparison purposes. The resulting in-plane resolutions are (a) $1.88 \times 1.88$ mm$^2$ and (b) $0.94 \times 0.94$ mm$^2$, with 4 mm through-plane slice thickness and $b = 500$ s/mm$^2$ for DW images. Note that the partial volume artifacts (the dark regions at the CSF boundary in ADC maps, as shown with the white arrows) are greatly reduced with reduced FOV ss-DWEPI due to higher resolution.

# In Vivo Imaging Results

Non-DW, isotropic DW,
and ADC maps for all three slices of the reduced FOV ss-EPI imaging

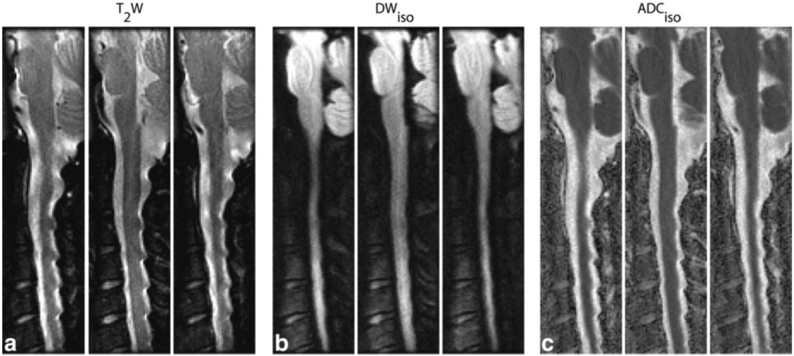



FIG. 4. Multi slice reduced FOV ss-DWEPI images of three adjacent slices. From left to right: (a) $T_2$ weighted images ($b = 0$), (b) isotropic DW images ($DW_{iso}$), and (c) corresponding $ADC_{iso}$ maps. ($b = 500$ s/mm$^2$, $0.94 \times 0.94$ mm$^2$ in-plane resolution, 4 mm slice thickness and 0.5 mm slice spacing). Note that only $DW_{iso}$ images are shown here, even though DW images in SI, AP, and LR directions were first reconstructed separately to later form the $DW_{iso}$ image.

# In Vivo Imaging Results

- Results of high-resolution axial DWI of cervical spinal cord with reduced FOV ss-EPI
- Demonstrate ability to acquire sub-mm DWI of spinal cord

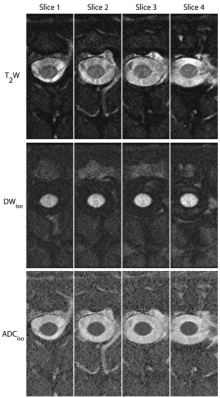



FIG. 5. Axial multi slice reduced FOV ss-DWEPI images of the cervical spinal cord. From top to bottom: $T_2$-weighted images, isotropic DW images ($DW_{iso}$), and corresponding ADC maps ($ADC_{iso}$) ($b = 500$ s/mm$^2$, FOV = 8 $\times$ 3 cm$^2$, 0.62 $\times$ 0.62 mm$^2$ in-plane resolution, 5-mm slice thickness and 0.5-mm slice spacing).

# Discussion

- Reduced FOV ss-EPI method excites minimum FOV to image ROI, reduces required k-space lines, and enables acquisition of higher resolution images for fixed scan time
- DW applied in three orthogonal directions reults in 10-minute scan time
- Can be extended to diffusion tensor imaging (DTI) for six or more directions and 15-20 minute scan time
- Compatibility with contiguous multi slice imaging is a significant advantage

# Discussion

- Fat suppression fails in certain regions due to bending in 2D echo-planar RF pulse only in non-axial images, because of large FOV in physical z-direction of scanner
- $B_0$ inhomogeneities become more pronounced with large FOV, resulting in bending of excitation profile when combined with long duration (16.8 ms) and concomitant fields from echo-planar gradients of 2D RF pulse
- Reduced FOV images with double resolution have quartered SNR