Reversed Spiral SENSE for fMRI

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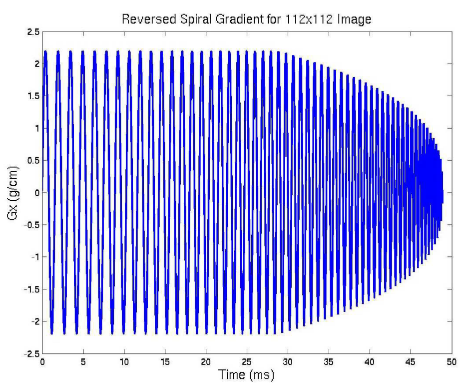
Introduction: Reducing the *k*-space sampling requirements with SENSE (1) has many advantages for fMRI including reduced image distortion, increased resolution, or increased coverage with a possible penalty in BOLD CNR (2,3). Furthermore, reversed spiral methods have been demonstrated to have potential advantages over forward spiral methods for fMRI including a more efficient use of scan time and reduced image blurring (4,5). A disadvantage of reversed spiral, however, is that image resolution limits the minimum TE, which could be problematic for higher resolution fMRI studies. In this work we propose a reversed spiral SENSE method for higher resolution fMRI. Images and activation maps at 3T using a four-channel coil and a *k*-space reduction factor of 2 are presented.

Theory: Reversed spiral methods acquire the maximum of *k*-space immediately after slice selection and spiral in to the center at TE. The acquisition time for one slice is equal to T_{RF}+TE, where T_{RF} is the RF pulse width. The reversed spiral readout time, therefore, has to be less than or equal to TE. Figure 1 (a) shows a reversed spiral readout gradient G_x for an 112x112 image acquisition with a 150 T/m/sec slew rate and 22 mT/m peak. The minimum TE with this readout is approximately 48 ms, a value longer than the typical 25-35 ms for fMRI at 3T. SENSE can be used to reduce the minimum TE for reversed spiral. For non-Cartesian SENSE, the image is reconstructed iteratively by minimizing a regularized cost function, using reduced *k*-space data from multiple receivers and maps of the coil spatial sensitivities. The *k*-space reduction is often parameterized by a reduction factor R. The readout can be reduced approximately by a factor R in a single-shot imaging modality with fixed resolution. Figure 1 (b) shows reversed spiral readout gradients for an 112x112 acquisition with a minimum TE of 23 ms.

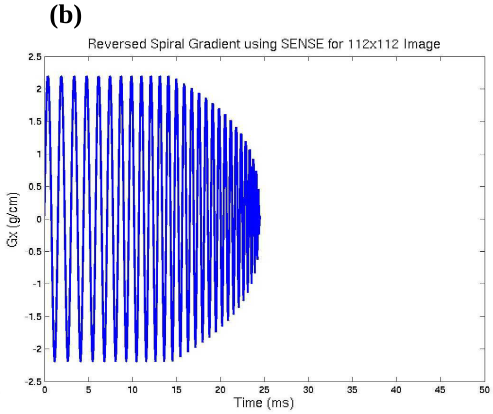
Methods: A multi-receiver reversed spiral sequence was written for a GE 3T scanner with a 150 T/m/sec slew rate and 22 mT/m peak. Normal human volunteers were scanned while performing a block design finger tapping task using forward and reversed spiral R=2 SENSE. The acquisition matrices were 96x96 and 112x112, which had minimum TE's of 18 and 23 ms, respectively. The slice orientation was axial and the thickness was 5 mm. Twenty slices were scanned per one second TR with a 60^0 flip angle. Image reconstruction was performed offline using an iterative reconstruction method with an external field map to reduce off-resonance related blurring (6,7). Activation maps were generated by a t-test with a temporal lag to account for hemodynamic delay.

Results: Figure 1 (c) and (d) show examples of 112x112 resolution images and activation maps (windowed between t=–1 and 1) from a subject performing the motor fMRI scan. The activation pattern is seen to follow the motor strip in the brain. Figure 1 (e) and (f) show a comparison between inferior slices acquired with forward and reversed spiral SENSE, respectively. By visual inspection the reversed spiral SENSE image shows more signal in the sinus region.

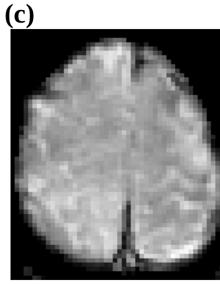
(a)



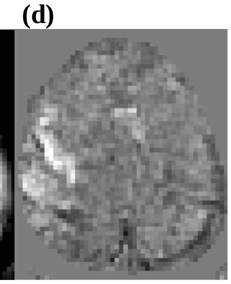
(b)



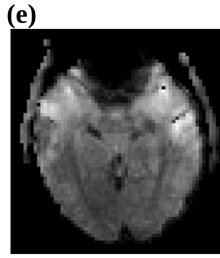
(c)



(d)



(e)



(f)

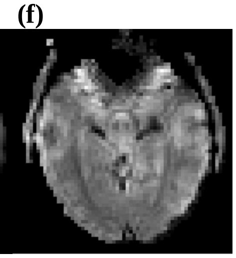


Figure 1: Reversed spiral gradients for 112x112 acquisition without **(a)** and with **(b)** R=2 SENSE. The minimum TE's are 48 and 23 ms, respectively. Reversed spiral SENSE motor fMRI 112x112 image **(c)** and activation map **(d)**. The activation is seen to clearly follow the motor cortex at this resolution. Forward **(e)** and reversed **(f)** spiral SENSE inferior 96x96 slices.

Conclusions: SENSE can be effectively combined with reversed spiral to create a time efficient method for acquiring single-shot high-resolution fMRI data. Images and activation maps with 112x112 resolution and a 23 ms TE were acquired at 20 slices per second. Although acquisition rates upwards of 27 slices per second were possible, gradient duty cycle restrictions on the scanner were the limiting factor. Another possible application of SENSE would be to reduce readouts and decrease the hardware demands of reversed spiral. The reduced gradient demands provided by SENSE can increase the slice throughput. A drawback of the method is the long image reconstruction time.

References: (1) Pruessmann *et al.*, MRM 1999; 42:952-962. (2) deZwart *et al.*, MRM 2002; 48:1011-1020; (3) Weiger *et al.*, MRM 2002; 48:860-866; (4) Bornert *et al.*, MRM 2000; 44:479-484; (5) Glover *et al.*, MRM 2001; 46:512-522; (6) Pruessman *et al.*, MRM 2001; 46:638-651; (7) Sutton *et al.*, IEEE TMI 2003; 22: 178-188.

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