Partial k-space acquisition method for improved SNR efficiency and temporal resolution in 3D fMRI

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Introduction: Previous studies have shown the relative importance of physiological noise and thermal noise in 2D MR images (1). Since physiological noise is proportional to the signal, it is the dominant component at the center of k-space. In partial k-space methods (2), the high spatial frequency components are doubled, resulting in twice as much noise from those components. However in sum these contributions are relatively small compared to those at the low spatial frequencies where physiological noise is dominant. Therefore, an improved SNR efficiency and temporal resolution can be achieved since the SNR benefit from increased time frames overcomes the SNR decrease from the partial k-space method itself.

Theory: Let (k_l, k_m, k_n) denote the position of a sampling point. Then the k-space noise at that point is

$$\sigma_k = \sqrt{\sigma_T^2 + \sigma_P^2} = \sqrt{\sigma_T^2 + (\lambda S(k_l, k_m, k_n))^2} ,$$

where λ is a proportional constant. The noise in the image space is given as

$$\sigma_{im} = \sqrt{\frac{1}{N_x N_y N_z} \sum_{l,m,n} [w(n)\sigma_k(k_l, k_m, k_n)]^2} ,$$

where w(n) is the filter used to smooth the transition and generate the corresponding weighting for the partial-k method. N_z is the reconstruction matrix size in the slab-select direction. Given the same scan time, the SNR efficiency ratio of the partial-k method over the full-k method is given as

$$\frac{SNR_{pk}}{SNR_{fk}} = \frac{\sigma_{im,\,fk}\sqrt{N_{z,\,fk}}}{\sigma_{im,\,pk}\sqrt{N_{z,\,pk}}} ,$$

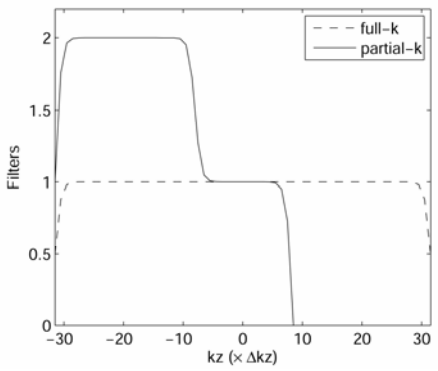


Figure 1. The filters for image reconstructions use Fermi function for transitions. In the partial-k method, 40 out of 64 k-space lines are collected.

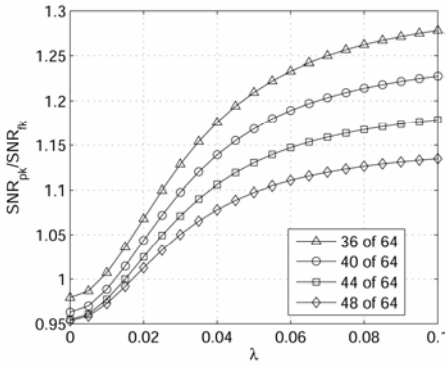
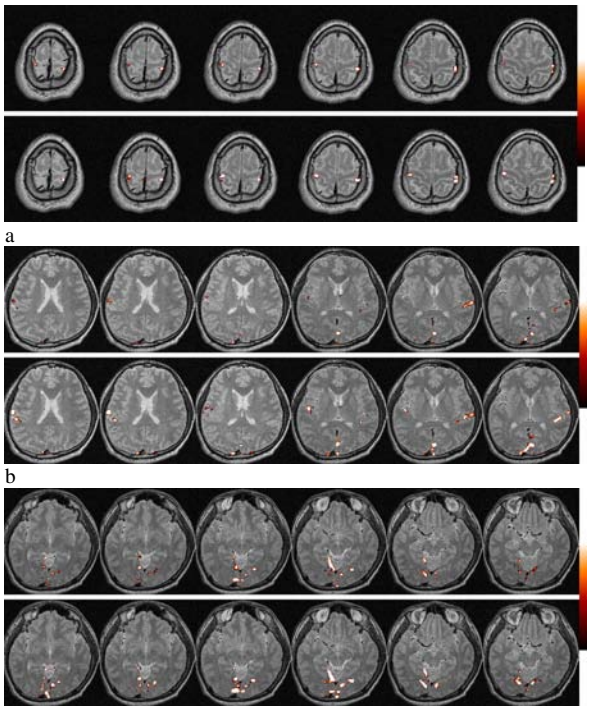


Figure 2. The effect of physiological noise and the number of k-space lines collected on the SNR efficiency (SNR_{pk}/SNR_{fk}).

where $N_{z,\,fk}$ and $N_{z,\,pk}$ are numbers of k-space planes collected for full-k and partial-k methods respectively. Simulations were performed based on the thermal SNR in the reconstructed images (~80) and the measured constant λ (~0.03). The object is assumed to have a rectangular shape which fills 0.6 of the field of view (FOV) in all three dimensions. The results are shown in Fig. 2. Although reducing the k-space coverage will result in higher SNR efficiency, a minimum number of k-space lines (40 of 64) is needed to produce reasonable images.

Methods: Experiments were performed on a 1.5T scanner equipped with the manufacturer's head coil (Signa, GE Medical Systems, Milwaukee, WI). A 3D stack-of-spirals trajectory (3,4) was used to cover k-space. In the slab-select direction, the excited slab thickness was 93mm with a FOV of 96mm and slice thickness of 1.5mm. Two end slices were discarded to reduce aliasing artifacts. TR was 100ms and the scan time per time frame was 6.4s. Flip angle was set to be Ernst angle (27°) to maximize the signal. The in-plane trajectory is a single shot, uniform density spiral with an echo time of 40 ms, in-plane FOV of 22 cm and in-plane effective matrix size of 64 by 64. 50 time frames were collected for rest state scans and 80 time frames were collected for functional scans with a block design of 20s-on/20s-off and a task of a contrast-reversing checkerboard visual stimulus and bilateral sequential finger apposition paced by auditory cueing tones at 3Hz supplied through earphones. The same set of data was used in the comparison to remove the behavioral difference in different scans. To make the effective scan time the same, only 5/8 of time frames with full-k coverage and all time frames but with only 5/8 of the k-space coverage were used for full-k and partial-k methods respectively for functional studies.



a

b

c

Figure 3. The comparisons of motor, auditory and visual activations between the full k-space method (top row) and the partial k-space method (bottom row) are shown in a, b and c respectively.

Results: Rest state studies showed that the average SNR increase is 8.8% among 6 volunteers. The comparisons of functional results in the motor, auditory and visual area from a representative volunteer are shown in Fig. 3. In each comparison, the top row depicts the activation maps using the full k-space method and the bottom row is the activation maps using the partial k-space method. The scale of p-values, which is from 0.01 to 0.0005, is the same for all figures. The total activated voxels and the corresponding average t scores are 983, 3.51 for the full k-space method and 1452, 3.84 for the partial k-space method respectively. Paired 2-tails Student T tests were calculated using functional data from all 7 volunteers, showing significant differences in the number of activations ($p = 0.004$, 0.0005 and 0.014 for motor, auditory and visual activations respectively) between full-k and partial-k methods.

Discussion: Experiments have shown advantages of the partial-k method over the full-k method in detecting neuronal activation. Although the technique was tested using a 3D stack-of-spirals trajectory, it is also applicable to fMRI studies using EPI trajectories as long as reduced number of k-space lines collected can result in a reduced number of RF excitations (scan time). In the simulation, special care was needed and the values of parameters should be determined based on the raw data. Behavioral difference in different scans could be large even for the same volunteer. Therefore the comparison should be the fairest if we use the same set of data but keep the effective scan time the same. Low SNR and low temporal resolution are the problematic issues in the high resolution fMRI studies. The 3D method has the benefit of increased SNR compared to the multi-slices 2D method especially when the number of slices is large. Partial k-space method can further increase the SNR efficiency and the temporal resolution. Thus, the combination of two techniques may provide a possible way of doing high resolution fMRI studies over the whole brain within a reasonable amount of scan time.

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