Increasing the sensitivity to BOLD contrast in high resolution fMRI studies by using 3D spiral technique

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Introduction: The main limitations for high resolution BOLD fMRI are low signal to noise ratio (SNR) and long volume scan time. Here our efforts were focused on improving the SNR of high resolution fMRI scans by switching to 3D acquisition methods [1, 2]. Compared to 2D multi-slice methods, 3D stack-of-spiral methods in general can improve SNR performance due to volume excitation. In this work, the SNR ratio of the 3D method over the 2D method was calculated based on a model in which thermal noise dominates physiological noise. This is valid for high resolution scanning. Comparison of high resolution fMRI studies using 3D and 2D methods confirmed our calculation.

Theory: The Ernst angle is used to maximize the steady state signal. Then, the signal is $S \propto \Delta z\sqrt{(1-E)/(1+E)}$, where $E = \exp(-TR/T_1)$. Assume that the scan time for each single spiral trajectory is T_s, and then the effective TR is T_s for the 3D method. While for the 2D method, since slices are excited sequentially, the effective TR is N_zT_s where N_z is the number of slices. If thermal noise dominates physiological noise in the measurements, then $\sigma_{3D} = \sigma_{2D}/\sqrt{N_z}$ due to the inverse Fourier transform in the slab-select direction. Therefore the SNR ratio of the 3D method over the 2D method is

$$\frac{SNR_{3D}}{SNR_{2D}} = \sqrt{N_z \frac{(1-E_{3D})/(1+E_{3D})}{(1-E_{2D})/(1+E_{2D})}} .$$

Simulation results are shown in Fig. 1.

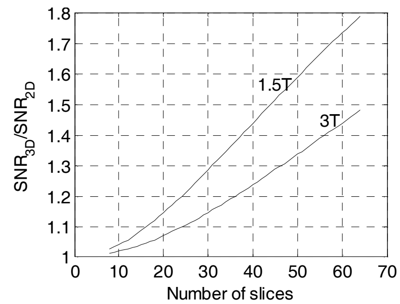

Figure 1: Calculated SNR ratio of the 3D method over its 2D counterpart. T_s=90ms, $T_{1,\,1.5T}$=900ms, $T_{1,\,3T}$=1350ms.

Methods: All experiments were performed on a 3T whole body scanner (Signa, rev 12M4, General Electric Medical Systems, Milwaukee, WI) with a 3in surface coil. Two functional scans using 2D multi-slice and 3D stack-of-spiral sequences were performed for each volunteer. Each scan lasted 4 minutes and 54 seconds. A contrast-reversing (3 Hz) checkerboard visual stimulus was used. T_s was set to be 90ms. 32-1mm slices were collected with TE of 30ms, an in-plane FOV of 14cm×14cm and a matrix size of 128×128. The nominal voxel size was 1mm×1.1mm×1.1mm.The flip angle was 83˚ and 21˚ for 2D and 3D methods respectively. Functional maps were overlaid on the T_2-weighted anatomic images.

Results: Table 1 lists the measured SFNR (time-series average signal divided by standard deviation) of gray matter for two methods. Although the absolute value of SFNR is affected by the non-uniform sensitivity of the surface coil, the SFNR ratio is not. The average SFNR improvement is 23% by switching to the 3D method, which is a bit higher than expectation (1.16). Fig. 2 shows the activation maps from a representative subject. Table 2 gives the number of activated voxels and the corresponding Z score for each subject. The 3D method does show better performance with regards to both the extent and strength of activation.

Subject	$SFNR_{2D}$	$SFNR_{3D}$	$SFNR_{3D}/SFNR_{2D}$
1	17.10	21.60	1.26
2	18.60	23.83	1.28
3	29.10	34.19	1.17
4	12.62	14.88	1.18
5	11.98	15.33	1.28
AVE±STD	--	--	1.23±0.05

Table 1: SFNR comparison between 2D and 3D methods

Discussion: Let $SNR_0 = S/\sigma_0$ be the thermal SNR and λ relate the physiological noise to the signal by $\sigma_p = \lambda \cdot S$, then $SNR = SNR_0/\sqrt{1+(\lambda \cdot SNR_0)^2}$. For gray matter, λ was found to be 0.012 [3]. In our experiments, the SNR is generally below 30. Then the SNR_0 should be smaller than 32 and the contribution from physiological noise is only 15% of that from thermal noise. Thus, our assumption that thermal noise dominates holds. The average measured SNR ratio here is 1.23 which is a bit higher than the expectation (1.16). One possible reason is that the gray matter filter used is not perfect. Contribution from white matter may exist in our analysis. White matter has a smaller T_1 (900ms) and thus a higher theoretical SNR ratio (1.32). The refocusing gradient of the RF pulse may also have an effect on this ratio. If it is not perfectly refocused, it causes signal drop for the 2D method. However for the 3D method, it only shifts the DC component (k_z=0) of k-space signal to the edge. Most of the signal in the image space will be recovered after the inverse Fourier transform as long as the DC component is still sampled. In summary, the 3D method demonstrates promise in high resolution fMRI.

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Subject	Number of activated voxels		Average Z score	
	2D	3D	2D	3D
1	408	1391	1.980	2.039
2	75	340	1.972	2.030
3	814	1419	2.006	2.068
4	6	46	2.009	1.935
5	686	1744	2.124	2.217
AVE±STD	398±359	988±746	2.040±0.062	2.109±0.082

Table 2: The numbers of activated voxels and corresponding average Z score detected by 2D and 3D spiral techniques.

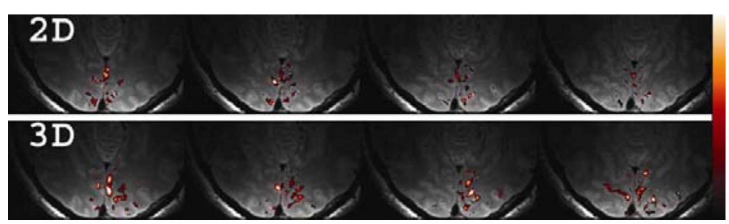

Figure 2: Comparison of activation maps from one representative volunteer between 2D and 3D methods. The scale of P-value is [0.0005, 0.05].

References:

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3. Kruger G, Glover GH. Physiological noise in oxygenation-sensitive magnetic resonance imaging. Magn Reson Med 2001;46(4):631-637.