Simultaneous Multislice Acquisition using Rosette Trajectories (SMART):
A New Imaging Method for Functional MRI

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Introduction
In prior work (1), we showed that rosette k-space trajectories (2) have spectral properties similar to stochastic trajectories (3), for which on-resonant spins reconstruct accurately and off-resonant spins are randomly dephased into noise. Here, we introduce the Simultaneous Multislice Acquisition using Rosette Trajectories (SMART) method, a new rapid imaging method for dynamic MRI. In the SMART method, several slices are simultaneously excited and k-space data is acquired using rosette k-space trajectories. Slices are distinguished by using a gradient to modulate different slices to different resonant frequencies during acquisition. Signals from off-resonance slices are destroyed by using the off-resonance properties of the rosette acquisition while on-resonance slices reconstruct accurately.

Methods
Rosette k-space trajectories can be described by a rapid, one-dimensional sinusoidal oscillation that is slowly rotating in the kₓ-kᵧ plane. One parameterization is:

\[
k(t) = k_{\text{max}} \sin (2\pi t_1) e^{j2\pi f_2 t},
\]

where \( k(t) = k_x(t) + jk_y(t), t_1 \) is the rapid oscillation frequency and \( f_2 \) is the slower rotational frequency. A single-shot rosette acquisition is shown in Fig. 1. For spins within the spectral passband (FWHM = 40 Hz) the spin reconstruct accurately, and outside the signal intensity is dispersed into “noise.” Destruction of image intensity arises from two sources: first, there is destructive interference when k-space trajectories cross; and second, there is a randomization of the phase in k-space, which leads to a random dispersal of the remaining image energy across the image.

Fig 1. Single-shot rosette acquisition with parameters:
- 29 ms readout
- \( t_1 = 1106 \) Hz
- (32 cyc. oscillation)
- \( f_2 = 104 \) Hz
- (3 cyc. rotation)
- FOV = 20 cm
- 40x40 matrix
- spatial res. = 5 mm.

Three slices are simultaneously excited by using an RF pulse modulated by \((1 + 2\cos(\pi S \gamma G_z t))\), where S is the slice separation. A gradient is applied perpendicular to the slice planes \((G_z)\) during the rosette acquisition in order to shift the acquired slices to different resonant frequencies. The gradient strength is chosen to position the off-resonance slices at frequencies for which the residual signal intensity is minimized. By successively demodulating the received data to the appropriate frequencies, each of the excited slices can be visualized. The off-resonance slices are dispersed into “noise.” Because most of the signals in the off-resonance slices are stable, the “noise” will be stable over time and will not degrade fMRI time-series data. Additional stability is gained by removing low-frequency drifts and pulmonary variations from the k-space data.

An experimental functional MRI (fMRI) study was conducted using a sequential finger-thumb opposition task and a resting control state (24 s on/ 24 s off, repeated 4 times). The pulse sequence parameters were TE \( = 45 \) ms, TR \( = 600 \) ms, and FA \( = 40^\circ\). In addition to the triple-slice SMART acquisition, a single-slice study was acquired for comparison purposes. In the SMART acquisition, 5 groups of 3 slices (15 slices overall) were excited in each TR interval for an average acquisition rate of 25 slices/sec.

Results
Images for this fMRI study were acquired on a GE 1.5 T Signa Horizon Echo-Speed system. Fig. 2 contains images, activation maps, and maps of the time-series standard deviation (SD). The raw images show an increase in background “noise,” but activation maps and SD maps do not show a large increase in noise, indicating that most of this additional background “noise” is stable over time. Consequently, this “noise” subtracts away in a dynamic imaging study. After removing low-frequency drifts and pulmonary variations from the k-space data, the measured SD for the three-slice acquisition was found to be only 10% greater than that of the single-slice acquisition.

Fig 2. Raw images (a,d), activation maps (b,e) and time-series SD maps (c,f) for single-slice rosette and three-slice SMART acquisitions. Top row (a-c) is from single-slice excitation and bottom row (d-f) is one of three slices in a three-slice excitation.

Conclusions
We have demonstrated the ability of the single-shot SMART method to rapidly acquire fMRI data over the entire brain (15 slices in 600 ms). The SMART technique allowed more slices to be acquired in an fMRI study than would be possible based on pulse sequence timing considerations. Specifically, the average time to acquire a single image (40 ms) is less than the combined time for excitation, fat suppression, TE, readout and crushers (~80 ms). This approach results in a small noise penalty (~10%), but three times as many slices can be acquired.

References

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