A novel single-shot trapezoidal-gradient based Lissajous trajectory is proposed here to image the human brain. A feature of this trajectory is that its sampling points are located on a nonequidistant rectangular grid, which permits the usage of a 1-D optimal algorithms to increase the robustness and speed in image reconstruction. Another advantage of the trajectory is that two images with different effective echo time can be obtained within a single excitation, which might be used for fast T2* mapping. Baseline images were acquired, and functional activation experiments were performed on human brain to demonstrate the feasibility of the new sequence.

Introduction

A number of k-space trajectories have been developed and implemented to date using time-varying gradients for rapid MRI acquisition, including spirals (1), stochastic trajectories (2), rosettes (3), and circles (4). A sinusoidal Lissajous trajectory was recently studied with computer simulations (5), which demonstrated that Lissajous trajectories with certain sampling patterns have special geometric characteristics permitting fast image reconstruction with optimal gridding. The disadvantage of the sinusoidal Lissajous trajectory proposed in (5) is that it covers k-space in a non-sequential way, which would introduce significant global artifacts caused by T2 decaying effect on reconstructed images. Furthermore, the scanning speed of the sinusoidal gradient was somewhat slow due to a lack of fully making use of the gradient system. In this study we designed a trapezoidal-gradient based Lissajous trajectory, which covers k-space sequentially within a single excitation, while keeping the special geometric features of sinusoidal Lissajous trajectory.

Methods

Traditional sinusoidal Lissajous trajectories use two sine functions with different frequencies for the gradient waveforms:

\[ g_x(t) = g_{xx} \sin(2\pi f_2 t) \]
\[ g_y(t) = g_{yy} \sin(2\pi f_1 t) \]

where \( f_1 \) and \( f_2 \) are periods of the gradient waveforms. To increase the traveling speed along a Lissajous trajectory in k-space, we designed trapezoidal gradient waveforms:

\[ g_{x1}(t) = \begin{cases} R & 0 \leq t < G/G \rule[-0.5em]{0em}{2em} \\ G & G \leq t < T_2/2 - G/G \rule[-0.5em]{0em}{2em} \\ -G & T_2/2 - G/G \leq t < T_2/2 + G/G \rule[-0.5em]{0em}{2em} \\ -T_2/2 & T_2/2 + G/G \leq t \rule[-0.5em]{0em}{2em} \end{cases} \]

where \( T_x \) and \( T_y \) are periods of periodical waveforms \( g_x(t) \) and \( g_y(t) \), \( G \) and \( R \) are the maximum magnitude and slew rate of the gradients respectively. With fixed \( G \) and \( R \), the k-space coverage (and therefore the image resolution) is determined by \( T_x \) and \( T_y \). Fig. 1 illustrates the Lissajous trajectories generated by sinusoidal and trapezoidal-based gradients respectively. The sampling started at a corner of k-space and ended at a neighboring corner.

In our sampling pattern, all cross-points of the trajectory were sampled twice and the data was then split into two sets. Therefore, two images with different effective echo time were obtained for every slice. Two additional diagonal lines were scanned as reference scan at the beginning and the end of the trajectory for correcting artifacts generated by inaccurate sampling location, one of the main sources of ghosting artifacts in EPI. Different from other nonrectilinear acquisition pattern, the modified Shepp-Logan digital phantom was used to evaluate the sampling points according to the reference scan.

The pulse sequence was implemented on a GE 3T scanner with a bandwidth of 125 kHz, maximal gradient of 17.2 mT/m, and slew rate of 145 T/m/s. \( T_x \) and \( T_y \) were set to 960 and 952 ms respectively, so that 64x64 resolution was obtained with a FOV of 24 cm. The length of the acquisition window was approximately 56ms and the acquisition started at 10ms after RF excitation. Baseline images were acquired, and functional activation studies with a unilateral finger-tapping task were performed with slice thickness/gap of 5/1 cm, and TR of 1000ms.

Results

Baseline images of human brain are shown in Fig. 2, demonstrating the feasibility of the technique and the image quality. For each slice, two images with different effective TE were obtained from a single excitation. It can be seen that there are little visible artifacts in the images and the image quality is comparable to that of other fast imaging techniques. Fig.3 shows the activation maps obtained from the bilateral finger-tapping experiment, overlaid on corresponding T1-weighted images. Task-related brain activations are shown in the primary sensorimotor cortices, as well as in the supplementary motor area. Two activation maps with different effective TE were obtained for each slice.

Discussion

In the trapezoidal-gradient based Lissajous trajectory, there are about 14,500 sampling points, including the diagonal reference scan. However, the number of sampling points would be at least doubled for traditional sinusoidal Lissajous trajectory, which would be impractical for single-shot implementation. Long acquisition window would aggravate the artifacts introduced by off-resonance and T2 decaying effects. By choosing a proper ratio of \( T_y \) to \( T_x \), we made the trajectory traversing the k-space sequentially for both data sets so that the T2 decaying effect did not result in global artifacts.

The acquisition points around the center of k-space form a diagonal grid, thus the FOV of a reconstructed image is a square with edges parallel to the diagonal directions (Fig.4). When images are reconstructed on a Cartesian grid, replicas of the image may appear at four corners. The distance between a replica and the image is the expected length of FOV and they would not overlap with each other.

References


Fig. 2: Images reconstructed from (a) the first echo and (b) the respective second echo data acquired on a GE 3T scanner. The scaling factor of the second-echo images is twice as that of the first ones.

Fig. 3: Activation maps of a bilateral finger tapping task, generated by cross correlation with a threshold of 0.65 and overlaid on corresponding anatomical images. Two maps for each slice were obtained from two simultaneously acquired image time series of (a) the first echo and (b) the second echo data.

Fig. 4: Image reconstructed from simulated data using the modified Shepp-Logan digital phantom with the consideration of both T2-decaying and trajectory inaccuracy effects. The replicas can be found at four corners. The actual FOV is marked by dotted lines.