Super-resolved two-dimensional spatiotemporally-encoded single-scan MRI with spiral sampling

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Target audience

The target audience of present paper is basic scientists and clinical scientists who are interested in ultrafast MRI and reduced field of view imaging.

Purpose

Recently, a spatiotemporally encoded (SPEN) MRI approach based on linear frequency-swept excitation has been proposed to overcome the artifacts induced by various field perturbations in single-scan echo-planar imaging (EPI).[1,2] To accelerate the acquisition, the phase encoding dimension is always sub-Nyquist sampling, which will lead to aliasing artifacts and degrade the image quality. Meanwhile, this approach still utilizes a Cartesian trajectory to cover the k-space. This trajectory is intrinsically sensitive to motion because of long readout time and has low sampling efficiency. In addition, only the readout direction gradient contributes significant energy to the trajectory. By contrast, spiral method samples k-space with Archimedean or similar trajectory that begins at the k-space center and spirals to the edge. Spiral method has shorter readout time and reduced sensitivity to motion. In this study, we propose a spiral sampling method for two-dimensional (2D) SPEN single-scan MRI. It not only maintains the advantages of SPEN method, but also possesses an inherent immunity to aliasing artifacts and lower sensitivity to motion. As to super-resolved reconstruction, we propose a preprocessing method based on singular value decomposition.

Methods

The pulse sequence is shown in Fig. 1. The spiral trajectory with equidistant pacing of revolution is applied:

$$\begin{aligned} g_{ax} &= c\cos\left(\omega_0 t\right) - c\omega_0 t\sin\left(\omega_0 t\right), \\ g_{ay} &= c\sin\left(\omega_0 t\right) + c\omega_0 t\cos\left(\omega_0 t\right), \end{aligned} \tag{1}$$

where c and ω_0 are the amplitude and angular frequency of the spiral sampling gradient, respectively. The two 180° chirp pulses and the corresponding orthogonal gradients impose on the spins two quadratic phase profiles along the two orthogonal axes respectively.

The resulting signal can be expressed as following integral:

$$s(t_1,t_2) = \iint\limits_{FOV} \rho(x,y) e^{i\left[\frac{\gamma^2 G_{exc\_x}{}^2 x^2}{R_x} - \frac{\gamma^2 G_{exc\_y}{}^2 y^2}{R_y} + \gamma x \int_0^{t_2} g_{ax} dt + \gamma y \int_0^{t_1} g_{ay} dt\right]} dxdy\ , \tag{2}$$

where the frequency sweep rate of chirp pulse $R = \Delta O / T_{exc}$, and ΔO and T_{exc} are frequency bandwidth and duration of the chirp pulse, respectively. For 2D SPEN MRI, $s(t_1,t_2)$ corresponds to the spatial position of proton. Because the quadratic phase of spins wraps very quickly, it is difficult to reconstruct the image directly from Eq. (2). Therefore, before super-resolved reconstruction based on singular value decomposition, the quadratic phase is eliminated in advance.

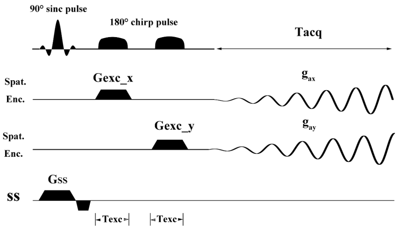

FIG. 1. 2D SPEN MRI pulse sequence with spiral sampling

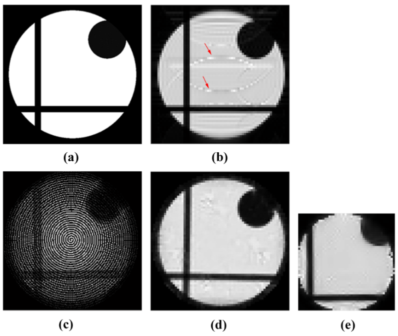

FIG. 2. (a) Simulation model; (b) super-resolved image reconstructed from conventional SPEN MRI; (c) modulus image from SPEN MRI with spiral sampling; (d) super-resolved image reconstructed from SPEN MRI with spiral sampling; and (e) super-resolved image reconstructed from SPEN MRI with rFOV spiral sampling. FOV = 6.0 × 6.0 cm^2 and data matrix = 64 × 64 for (b) and (d), FOV = 4.2 × 4.2 cm^2 and data matrix = 48 ×48 for (e). Same chirp pulses were used: T_{exc} = 3.0 ms, and ΔO = 64 kHz.

Results

Numerical simulations were conducted to verify the feasibility of 2D SPEN single-scan MRI with spiral sampling. The results are given in Fig. 2. Fig. 2c is the modulus image achieved by interpolating the data onto a uniform grid. The super-resolved image reconstructed from the spiral sampling data is shown in Fig. 2d. Compared to the super-resolved image reconstructed from conventional Cartesian sampling data (Fig. 2b), the image in Fig. 2d possesses comparable resolution but no aliasing artifacts. Fig. 2e shows the super-resolved image reconstructed from reduced field of view (rFOV) spiral sampling data.

Discussion

By using SPEN, the relationship between spatial position and sampling time is established during the acquisition. So interpolating the acquired data onto a uniform grid can directly give the profile of sample (Fig. 2c). For conventional SPEN MRI with Cartesian trajectory, the aliasing artifacts occur on the image along the phase encoding direction (indicated with red arrow in Fig. 2b) because of undersampling. Whereas for 2D SPEN MRI with spiral trajectory, the aliasing artifacts disappear since the spiral sampling is actually oversampling, especially in the center region of k-space. In combination with rFOV imaging scheme, spiral sampling can provide better temporal resolution without reduction of spatial resolution (Fig. 2e).

Conclusion

In summary, spiral sampling was introduced to 2D SPEN single-scan MRI. It can eliminate the aliasing artifacts occurred in conventional SPEN MRI with a Cartesian trajectory due to sub-Nyquist sampling. Combined with super-resolved reconstruction, it can produce images with higher resolution. Experimental verification is ongoing.

Acknowledgement

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References

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