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Original contributions

Reduced field-of-view imaging for single-shot MRI with an amplitude-modulated chirp pulse excitation and Fourier transform reconstruction☆

Jing Li [a], Miao Zhang [a], Lin Chen [a], Congbo Cai [b,*], Huijun Sun [a], Shuhui Cai [a,**]

[a] Department of Electronic Science, Fujian Provincial Key Laboratory of Plasma and Magnetic Resonance, Xiamen University, Xiamen, China
[b] Department of Communication Engineering, Xiamen University, Xiamen, China

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ABSTRACT

Purpose: We employ an amplitude-modulated chirp pulse to selectively excite spins in one or more regions of interest (ROIs) to realize reduced field-of-view (rFOV) imaging based on single-shot spatiotemporally encoded (SPEN) sequence and Fourier transform reconstruction.

Materials and Methods: The proposed rFOV imaging method was theoretically analyzed and illustrated with numerical simulation and tested with phantom experiments and *in vivo* rat experiments. In addition, point spread function was applied to demonstrate the feasibility of the proposed method. To evaluate the proposed method, the rFOV results were compared with those obtained using the EPI method with orthogonal RF excitation.

Results: The simulation and experimental results show that the proposed method can image one or two separated ROIs along the SPEN dimension in a single shot with higher spatial resolution, less sensitive to field inhomogeneity, and practically no aliasing artifacts. In addition, the proposed method may produce rFOV images with comparable signal-to-noise ratio to the rFOV EPI images.

Conclusion: The proposed method is promising for the applications under severe susceptibility heterogeneities and for imaging separate ROIs simultaneously.

1. Introduction

Ultrafast imaging is desired in the applications that require high temporal resolution, such as functional MRI [1–7], free-breath cardiac imaging [8] and high-dimensionality imaging (e.g. diffusion tensor imaging) [9–11]. Echo-planar imaging (EPI) is one of the most important ultrafast techniques and has been applied in many studies [12–14]. For single-shot EPI, full k-space lines are collected in a single shot to reduce the acquisition time. However, the extremely long echo-train length (ETL) in EPI reduces the image quality due to the occurrence of ghosts and ringing artifacts as well as geometric distortion [15–18].

Reduction of the total echo-train duration can be accomplished by reducing the ETL. However, the spatial resolution will be sacrificed to reduce the ETL. Reduced field-of-view (rFOV) imaging [19–21] along the PE direction can be used to reduce the number of phase encoding lines and hence reduce the ETL without compromising spatial resolution for those applications in which the region of interest (ROI) is only a small part of the FOV. Meanwhile, the strength of phase-encoding (PE) gradient increases in the rFOV imaging (gradient strength = bandwidth/($\gamma \cdot$ FOV), where γ is the gyromagnetic ratio), so the influence from the inhomogeneous field is relatively alleviated.

Several rFOV imaging techniques have been proposed, including spatial pre-saturation [22,23], orthogonal RF excitation [24,25], and two-dimensional spatially selective RF (2DRF) pulses excitation [26,27]. Spatial pre-saturation is usually sensitive to B_1 inhomogeneity, although some techniques have been used to improve the B_1 inhomogeneity tolerance [20,25]. For pulse sequences with long repetition time (TR) such as spin-echo EPI, another problem associated with spatial pre-saturation is that the T_1 recovery of the transverse magnetization in the saturation region during acquisition usually degrades saturation performance. For the rFOV imaging methods using orthogonal RF excitation [24,25] and 2DRF pulses excitation [27], aliasing artifacts will be generated if the excited area is larger than the imaged rFOV, especially in inhomogeneous field.

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* Correspondence to: C.B. Cai, Department of Communication Engineering, Xiamen University, Xiamen 361005, China.
** Correspondence to: S.H. Cai, Department of Electronic Science, Xiamen University, Xiamen 361005, China.
E-mail addresses: cbcai@xmu.edu.cn (C. Cai), shcai@xmu.edu.cn (S. Cai).

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Recently, a "Hybrid" spatiotemporally encoded (SPEN) MRI approach with a chirp pulse excitation was proposed to overcome the artifacts induced by various field perturbations in single-shot EPI [28–32]. The band-selective excitation also offers the SPEN approach an inherent applicability to rFOV imaging along the low-bandwidth dimension (corresponding to the PE direction in EPI) [33–36]. However, the rFOV SPEN image obtained with the existing method may be affected by the Gibb's ripple artifacts due to the truncation of high frequency signals at the two edges along the SPEN direction [33]. In addition, these rFOV imaging methods are generally restricted to one ROI in single-shot MRI. For body parts and organs distributed dispersedly, such as renal and limb imaging, at least two shots are needed for these rFOV imaging methods. Moreover, their reconstruction methods either need long processing time or result in spatial resolution reduction [33,34].

In this study, we further exploit the "Hybrid" encoding property of the SPEN sequence, i.e. the property of integrating spatial encoding with conventional k-space encoding [28,30,32,35]. During the excitation period T_{exc}, an amplitude-modulated chirp pulse together with an excitation/encoding gradient G_{exc} was used to realize selectively spatial encoding [28,30–32]. During the acquisition period T_{acq}, a series of blip gradients (G_{acq}) fulfilling the relation $|G_{acq}T_{acq}| = |G_{exc}T_{exc}|$ were applied along the SPEN dimension to acquire the SPEN signals contributed from the spins in spatially encoded FOV. In the SPEN MRI, it is convenient to obtain an original SPEN image by calculating the magnitude of the acquired SPEN signal, but this magnitude image is blurred, and its inherent spatial resolution is relatively low. Therefore, super-resolved (SR) reconstruction is indispensable to improve the resolution without additional acquisition [30,32,35]. Given that the blip gradients endow the SPEN sequence the property of conventional k-space encoding, it is feasible to apply Fourier transform (FT) to reconstruct the acquired SPEN signals and the final imaged FOV (L_{FT}) can be determined by $L_{FT} = 2\pi/(\gamma G_{acq}T_{blip})$, where T_{blip} is the duration of one blip gradient G_{acq}. Consequently, FT may not only improve the spatial resolution of original magnitude SPEN image as an SR algorithm, but also realize rFOV imaging and then further enhance the spatial resolution when proper experimental parameters are chosen. In addition, the amplitude-modulated chirp pulse offers the SPEN method an ability of imaging two or more separated ROIs simultaneously along the low-bandwidth dimension in a single shot.

2. Material and methods

The single-shot "Hybrid" SPEN pulse sequence used in the study is shown in Fig. 1, in which the parameters (e.g. G_{exc}, G_{acq}, etc.) are indicated. For simplicity, a one-dimensional imaging along the y direction is taken as an example to illustrate the principle of the sequence. During the encoding period T_{exc}, an amplitude-modulated 90° chirp pulse combined with an encoding gradient G_{exc} imposes on the spins a quadratic phase with relation to the position y along the SPEN direction [30–32,37]. During the decoding period, a series of decoding blip gradients (G_{acq}) are applied over an acquisition period T_{acq}, which fulfills the relationship $|G_{exc}T_{exc}| = |G_{acq}T_{acq}|$ (thereby allowing the signals from the spins in the encoded FOV (L_y) to be detected).

2.1. Amplitude-modulated chirp pulse

As mentioned above, the single-shot SPEN sequence imparts a quadratic y-dependent phase on the spins along the low-bandwidth dimension by applying a linear frequency swept (chirp) pulse at the presence of a y-oriented encoding gradient G_{exc}. The chirp pulse has a time-dependent angular frequency $\omega_c(t)$ and can be described by [31]:

$$\boldsymbol{B}(t) = B_1(t)\left\{\cos[\phi_c(t)]\hat{\boldsymbol{x}} + \sin[\phi_c(t)]\hat{\boldsymbol{y}}\right\}, \tag{1}$$

where $B_1(t)$ has a slowly varying profile and can be modulated. $\phi_c(t)$ is the accumulated phase due to the chirp pulse [31]:

$$\phi_c(t) = \int_0^t \omega_c(t')dt'. \tag{2}$$

If $\omega_c(t)$ varies with time as $\omega_c(t) = O_i + Rt$, the pulse is regarded as linearly chirped, where O_i is the initial sweep frequency (in, e.g., rad/s). During the excitation period, the chirp pulse has a well-defined instantaneous frequency at each instant, $\omega_c(t) = d\phi_c/dt$ [31]. Hence, at a certain time t_e, the chirp pulse only affects those spins with an on-resonance frequency equal to $\omega_c(t_e)$, and tips them around the direction of RF field onto the transverse plane. It is feasible to modulate the profile $B_1(t)$ of chirp pulse to selectively excite the spins in ROI to the transverse plane and not tip the spins outside the ROI to the transverse plane. Different kinds of amplitude-modulated chirp pulse and their characteristics are shown in Fig. 2. We can see that the chirp pulse modulated by a continuous amplitude profile (Fig. 2a and b) can excite the spins in a continuous region (Fig. 2g and h). The excitation of spins in two or more disperse regions can be realized by the chirp pulse shown in Fig. 2c. This band-selective excitation offers an inherent applicability to the rFOV imaging along the low-bandwidth dimension (corresponding to the PE direction in EPI).

2.2. FT reconstruction

For the "Hybrid" SPEN sequence shown in Fig. 1, the quadratic y-dependent phase imposed on the spins in the FOV (L_y) can be expressed as [30,32]:

$$\phi_{exc}(y) = -\frac{\gamma G_{exc}T_{exc}}{2L_y}y^2 + \frac{\gamma G_{exc}T_{exc}}{2}y - \frac{\gamma G_{exc}T_{exc}L_y}{8} - \frac{\pi}{2}. \tag{3}$$

Assume that G_{acq} is constantly applied over an acquisition time T_{acq} and $|G_{exc}T_{exc}| = |G_{acq}T_{acq}|$, an additional phase $\phi_{acq}(y,t) = \gamma\int_0^t G_{acq}(t')dt' \cdot y = \gamma G_{acq}t \cdot y$ is added onto the spins, and the entire acquired signal based on the "Hybrid" SPEN sequence shown in Fig. 1 can be calculated using the following integral [36,38]:

$$s(t) \propto \int_{-L_y/2}^{L_y/2} \rho(y) e^{i\left(\frac{\gamma G_{exc}T_{exc}}{2L_y}y^2 - \frac{\gamma G_{exc}T_{exc}}{2}y + \frac{\gamma G_{exc}T_{exc}L_y}{8} + \frac{\pi}{2} + \gamma G_{acq}t \cdot y\right)} dy. \tag{4}$$

Let $k_{SPEN}(t) = -\gamma G_{exc}T_{exc}/2 + \gamma G_{acq} \cdot t = -\gamma G_{acq}T_{acq}/2 + \gamma G_{acq} \cdot t$ when $t \in [0, T_{acq}]$, or let $k_{SPEN}(t) = \gamma G_{acq} \cdot t$ when $t \in [-T_{acq}/2, T_{acq}/2]$. According to the property of k-space encoding, Eq. (4) can be expressed as

$$s(n\Delta k_{SPEN}) \propto \int_{-L_y/2}^{L_y/2} \rho'(y) e^{in\Delta k_{SPEN} \cdot y} \cdot dy, \tag{5}$$

or

$$s(k_{SPEN}(t)) \propto \int_{-L_y/2}^{L_y/2} \rho'(y) e^{ik_{SPEN}(t) \cdot y} \cdot dy, \tag{6}$$

where $\rho'(y) = \rho(y) e^{i\left(\frac{\gamma G_{exc}T_{exc}}{2L_y}y^2 + \frac{\gamma G_{exc}T_{exc}L_y}{8} + \frac{\pi}{2}\right)}$; n represents the nth decoding position (i.e. sampling point), and Δk_{SPEN} is the acquisition