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A dual K-space UNFOLD method for 3D functional brain imaging: A preliminary study

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ABSTRACT

Purpose: To investigate a method of dual k-space unaliasing by Fourier-encoding the overlaps using the temporal dimension (DUNFOLD), a novel technique for high temporal resolution 3D functional brain imaging.

Methods: Two different methods of unaliasing by Fourier-encoding the overlaps using the temporal dimension (UNFOLD), excitation UNFOLD (XUNFOLD) and acquisition UNFOLD, were merged to obtain a DUNFOLD. The feasibility of the DUNFOLD technique was examined by using a phantom and comparing its result to that of the previous XUNFOLD method. A high temporal resolution 3D functional brain imaging study was also performed, focusing on the microvascular response. Three different temporal resolutions, 20 s, 10 s and 5 s, were tested with a spatial resolution of 0.6^3 mm^3 to evaluate the method. The vascular regions of interest were selected for data analysis.

Results: The DUNFOLD method achieved a temporal resolution approximately four times greater than those of the UNFOLD and XUNFOLD methods, without apparent signal degradation. The vascular responses in the visual cortex were obtained with high spatiotemporal resolution by using the DUNFOLD method during visual stimulation. For small vessels, the percentage change in the signal reached 18%.

Conclusion: The proposed DUNFOLD method yields a temporal resolution higher than those of the previous UNFOLD and XUNFOLD methods. The conclusions are likely to be important for functional imaging studies, especially those targeting cerebral vascular responsiveness.

1. Introduction

Fast imaging techniques for dynamic imaging have attracted significant interest for both clinical and research applications [1–5], and various fast imaging methods, such as partial k-space methods and unaliasing by Fourier-encoding the overlaps by using the temporal dimension (UNFOLD) technique, were introduced to improve the temporal resolution [6–11]. Partial k-space methods acquire only a part of the k-space data and fill the rest with several different variations [6–9], whereas UNFOLD-based techniques acquire the aliased images periodically since they under-sample along the phase-encoding direction and then eliminate the aliasing components in the temporal frequency domain [10,11].

Recently, a method combining the UNFOLD technique [12] with a local excitation technique [13] was developed, in which the weighted echo planar excitation trajectory can guarantee a reasonable radio-frequency (RF) pulse duration. The local excitation restricts the excitation volume so that this technique can be used to further enhance the temporal resolution. The single-shot based approach, however, still has a limitation related to the local excitation design [14,15]. Therefore, the excitation UNFOLD (XUNFOLD) method was introduced, extending the UNFOLD method into the excitation k-space domain and providing a solution to the long RF duration, which was an intrinsic and troublesome property of the local excitation in previous dynamic studies [16]. Although these attempts have yielded improved temporal and spatial resolutions, further temporal resolution enhancement is necessary for higher resolution 3D functional brain imaging studies.

In this study, we combined the UNFOLD method with the XUNFOLD method and evaluated the feasibility of applying the new method to 3D functional brain imaging, especially its ability to investigate arterial responses with higher spatial and temporal resolutions.

2. Methods

2.1. DUNFOLD concept

Using the UNFOLD method to increase the temporal resolution by acquiring a periodically shifted and reduced k-space produces

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periodic time-dependent aliased images. The time varying shift induces a corresponding phase change in the time domain and produces a frequency shift of the aliasing components in the temporal frequency domain which can be removed simply by filtering [10].

The temporal resolution can be also enhanced by restricting the excitation volume by applying a spatially selective 2D RF pulse. However, a single-shot based 2D RF pulse has a relatively long RF duration. To reduce the RF duration, a multi-shot local excitation method was developed, in which the excitation trajectory can be decomposed into several interleaved shots [15]. In XUNFOLD, the temporal frequency filtering concept is extended to the interleaved excitation profiles [16].

In this study, the UNFOLD and XUNFOLD methods were combined to further improve the temporal resolution; the new method is called the dual k-space UNFOLD (DUNFOLD) method. Since its Fourier transform property causes identical under-sampling effects in both excitation k-space and acquisition k-space domains, the aliased components can be superimposed by carefully designing the sampling parameters so that both aliasing components can be filtered out simultaneously. Fig. 1 shows the schematic of the DUNFOLD method as well as the previous UNFOLD methods. Phase encoding (PE) directions for under-sampling were predefined in the acquisition and excitation k-spaces. Note that the PE directions in the excitation k-space are denoted K_1 and K_2 to avoid confusion with the PE directions in the acquisition k-space, K_{PE} and K_{SL}. Spiral and Cartesian sampling trajectories were utilized for excitation and acquisition, respectively. The amplitudes of the DC components in the temporal frequency spectrum were also assigned arbitrary values. Fig. 1(a) illustrates the UNFOLD method with a reduction factor (f_A) of 4. In this method, the aliasing components are induced by the under-sampling in the acquisition k-space (arrows). In the XUNFOLD method, the aliasing components are induced by under-sampling in the excitation k-space, as shown in Fig. 1(b).

In the DUNFOLD method, using the periodic nature of the image profiles induced by the periodically shifted under-sampling, which is identical in the two domains, the XUNFOLD aliasing components can be exactly superposed on those caused by the data under-sampling in the acquisition k-space of UNFOLD, as shown in Fig. 1(c). To eliminate all aliasing components simultaneously, both aliasing harmonics should be manipulated so that they share the same filtering region with the simple criterion $R = \frac{\max(f_E, f_A)}{\min(f_E, f_A)}$, where R is the reduction ratio, which should be designed to be an integer; f_E is the number of interleaved shots used for the excitations; and f_A indicates the amount of under-sampling in the data acquisition process. Then, the aliasing components, of which there are finite numbers, are superimposed and simply eliminated along with the corresponding frequency spectrum.

When stimulation protocols are presented, the number of sessions (n_s), number of frames per session (n_t), temporal resolution (T), and session duration (T_s) determine the temporal frequency spectrum of functional voxels, as shown in Fig. 2(a). Note that n_s and n_t should be selected to preserve the functional information from the temporal domain filtering [10]. The temporal frequency spectra are shown in Fig. 2(b), (c), and (d) for static voxels and functional voxels without and with under-sampling, respectively. Because static voxels show no responses to external stimulation, only the DC component can be measured in the temporal frequency spectrum (Fig. 2(b)). However, functional voxels respond to stimulation and exhibit different spectral patterns. For simplicity, we chose $n_t = 5$ in the stimulation protocol, and the five corresponding peaks were located at the harmonics of the fundamental frequency ($1/T_s$) (Fig. 2(c)). Note that the spectral intensities necessary for simple visual perception are assigned arbitrary values in this method. Functional voxels with under-sampling exhibit even more complicated spectra. Aliasing components induced by the k-space under-sampling ($f_A = 2$) are added to the temporal frequency spectrum (Fig. 2(d)). However, the positions of the aliasing components in the

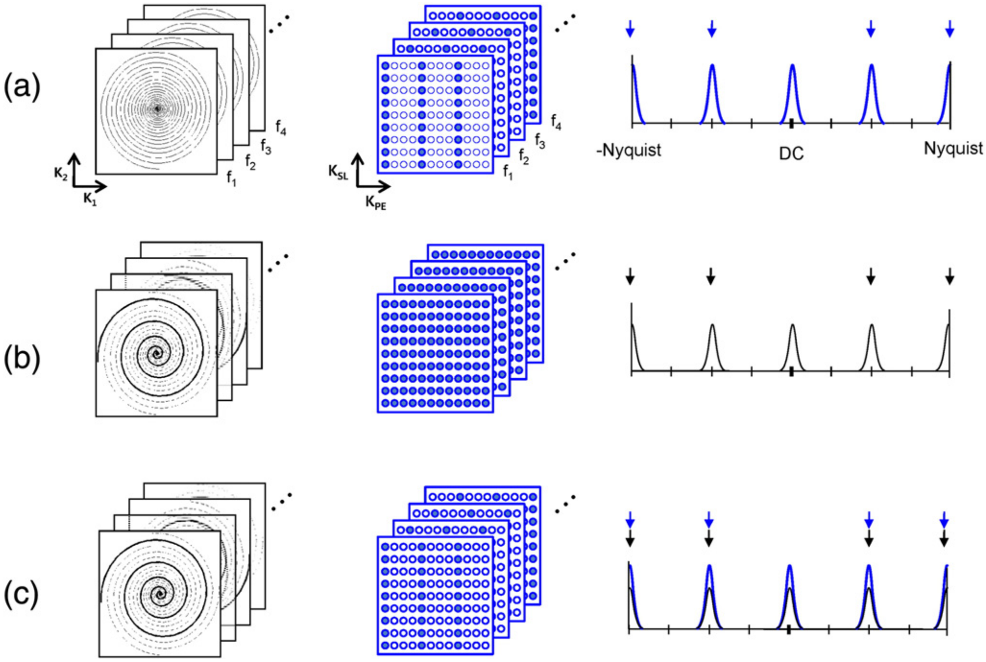

Fig. 1. Simplified concept of DUNFOLD method. (a) UNFOLD method with reduction factor 4 ($f_A = 4$). (b) XUNFOLD method with 4-shot interleaved design ($f_E = 4$). (c) DUNFOLD method with 4-shot interleaved design and reduction factor 4, i.e., $f_A = 4$ and $f_E = 4$ simultaneously ($f_A/f_E = 4/4$). Left, middle and right columns indicate excitation k-space, acquisition k-space and temporal frequency spectrum, respectively. Blue and black colors in right column indicate data acquisition and excitation spectra, respectively. Note that the frequency encoding (FE) was omitted for simplification. Abbreviations: K_1 and K_2, excitation k-space; K_{SL} and K_{PE}, acquisition k-space; f_1–f_4, frames (volumes) in time; Nyquist, Nyquist frequency.