Faster SPEED Imaging with Ghost Location Information from Central k-Space

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Target audience: Researchers and clinicians interested in fast MRI, novel data acquisition strategies, and reconstruction algorithms.

Purpose: Skipped Phase Encoding and Edge Deghosting (SPEED) is able to accelerate MRI with only a single coil. SPEED under-samples k-space and acquires data at every Nth line along phase encoding (PE) [1, 2]. Traditionally, three such datasets were acquired in an interleaved fashion with different PE offsets in order to resolve a two-layer signal model in the reconstruction process. In this study, we propose an improved version of SPEED that requires only two interleaved datasets. This method is termed C-SPEED as it extracts unused information from central k-space that was previously acquired only for inverse filtering in SPEED reconstruction. Results from phantom and *in vivo* data demonstrated the feasibility of the proposed method, leading to further acceleration compared with original SPEED imaging.

Methods: Spin-echo MRI slices in various anatomical regions and orientations were used, including axial head, saggital knee, and coronal hip, all acquired on 1.5 T whole body clinical scanners, with a k-space matrix size of 256×256. The full data were sparsely sampled into two interleaved datasets $S_1(\mathbf{k})$ and $S_2(\mathbf{k})$ with a PE skip size N, and PE offsets d_1 and d_2. A band of 32-64 lines near k-space center was acquired as $S_c(\mathbf{k})$ for both inverse filtering [1, 2] and finding the ghost order index pair (n_1, n_2) needed to resolve ghost overlapping. The C-SPEED reconstruction was implemented with the following steps:

(1) The central k-space data band $S_c(\mathbf{k})$ was zero padded to cover the entire k-space, and Fourier Transformed (FT) to form a low resolution image $I_c(\mathbf{r})$;

(2) A differential operation was performed on $I_c(\mathbf{r})$, producing a sparse edge image $E_c(\mathbf{r})$;

(3) Displace $E_c(\mathbf{r})$ along PE direction with different shifts in steps of FOV/N to yield N low resolution ghosted edge maps $E_{c,n}(\mathbf{r})$, where $n = 0, 1, 2, \ldots, N-1$ (This "*n*" is the so-called "ghost order index" indicating the order of the ghost);

(4) At each pixel, identify the two most intense ghosts among the N ghosts maps $E_{c,n}(\mathbf{r})$ and record their ghost order indices (n_1, n_2);

(5) Similar to (1) and (2), the two interleaved datasets $S_1(\mathbf{k})$ and $S_2(\mathbf{k})$ were reconstructed by FT into two full resolution ghosted images $I_1(\mathbf{r})$ and $I_2(\mathbf{r})$, and subsequently turned into ghosted sparse edge maps $E_1(\mathbf{r})$ and $E_2(\mathbf{r})$ by a differential operation;

(6) Using $E_1(\mathbf{r})$, $E_2(\mathbf{r})$, and (n_1, n_2), two dominating overlapping ghosts G_{n1} and G_{n2} can be solved from the 2-layer ghost equations blow,

$$\begin{aligned} E_1 &= P_{d1}^{n1} G_{n1} + P_{d1}^{n2} G_{n2} \\ E_2 &= P_{d2}^{n1} G_{n1} + P_{d2}^{n2} G_{n2} \end{aligned} \quad , \quad P_d^n = e^{i(2\pi dn/N)}, \quad d = 0, 1, 2, \cdots, N-1; \quad n = 0, 1, 2, \cdots, N-1; \qquad (1)$$

where *d* and *n* are now known integers representing the relative sampling shifts in PE and the ghost indices found in step (4);

(7) Sort out the resolved ghosts according to their ghost order index, yielding N separate ghost maps $G_n(\mathbf{r})$, n = 0,1,…, N-1;

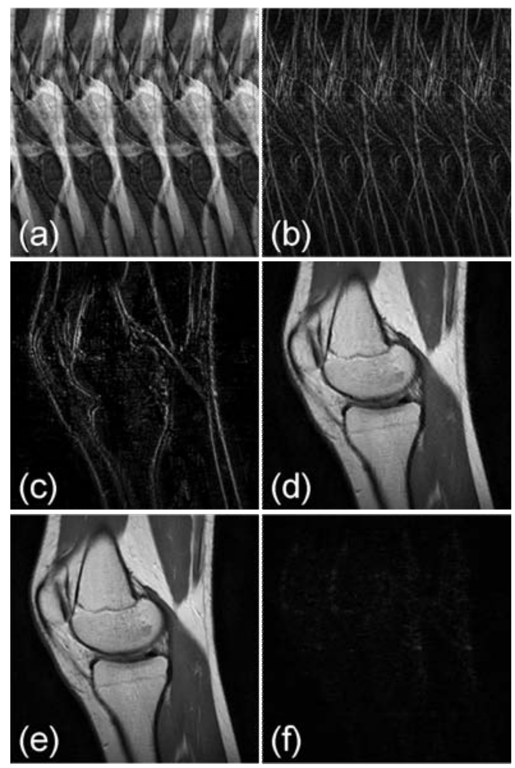
(8) All of the separate ghost maps $G_n(\mathbf{r})$ were registered and added together to produce a single deghosted edge map $E_0(\mathbf{r})$;

(9) $E_0(\mathbf{r})$ was inverse Fourier transformed back to k-space, and inverse filtered, then with its central part replaced by the acquired data $S_c(\mathbf{k})$;

(10) Finally, a deghosted image $I_0(\mathbf{r})$ was reconstructed with another Fourier transformation.

Steps (7-10) were described before [1, 2]. The new material was mainly the way of finding the ghost order indices (n_1, n_2) and solving the ghost equations. The full k-space data were also reconstructed by standard FT into a "gold-standard" image $I_g(\mathbf{r})$ for comparison. Reconstruction errors were quantified by using the Total Relative Error (TRE) [2] as defined by Eq.(2),

$$TRE = \sqrt{\sum_{x,y}\left[I_0(x,y) - I_g(x,y)\right]^2 / \sum_{x,y} I_g(x,y)} \qquad (2)$$



Results: Figures (a-g) present partial results of C-SPEED on sagittal knee data, similar results were obtained with data from axial head and coronal hip. Fig.(a) is reconstructed from one of the two interleaved datasets with a direct FT and differential operation, with five-fold ghosting because of the PE skip size N = 5. Fig.(b) is the corresponding edge map *E* after differential operation, with much reduced chance of ghost overlapping, therefore can be modeled by Eq.(1). Fig.(c) is the edge map $E_0(\mathbf{r})$ after deghosted by resolving the two layers of ghosts, followed by registration and summation. Fig.(d) is the final deghosted image $I_0(\mathbf{r})$. Fig.(e) is the gold-standard image from full k-space data. (f) is an error map obtained as the absolute difference between (d) and (e). The TRE of Fig.(e) was only (3.65e-4), suggesting a reasonably high reconstruction quality.

Discussion: Although the ghost order index map (n_1, n_2) was obtained with a low resolution image from central k-space, it served well to resolve high resolution images because ghost orders can only be the N possible integers that vary regionally representing a local group of pixels. The proposed C-SPEED is faster as it samples two instead of three datasets, it can also use a flexible skip size N similar to the Generalized-SPEED [2].

Conclusion: The time efficiency of SPEED has been improved by more exhausted use of central k-space data.

References: (ACKNOWLEDGEMENT: NSFC Grant 61372024)

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[2] Jin Z and Xiang Q-S, Accelerated MRI by SPEED with generalized sampling schemes, MRM, published on line, DOI: 10.1002/mrm.24605