General Skipped Phase Encoding and Edge Deghosting (SPEED) with Flexible Data Acquisition

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Introduction The fast imaging method of Skipped Phase Encoding and Edge Deghosting (SPEED) acquires skipped k-space lines [1], in a manner similar to SENSE [2] and GRAPPA [3]. Typically, three interleaved datasets with different PE shifts allow reconstruction by using a two layer signal model. The skip size N was previously chosen to be a prime number only, such as N = 5, 7, 11, in order to avoid reconstruction difficulty due to possible ghost phase degeneracy [1, 4]. In this study, we demonstrated that N does not have to be limited to prime numbers, and composite numbers with appropriately selected PE shifts can result in satisfactory reconstruction as well. Combinations between N and PE shifts determine the quality of reconstruction, which can be reflected in the condition number of a phasor matrix [1]. High quality reconstruction was achieved with composite skip sizes at N = 4, 6, 8, 9 and 10. These new possibilities in data acquisition provide SPEED with more flexibility in terms of practical implementations and applications.

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. While other imaging parameters may vary, the k-space data matrices were 256×256 in size. The full data were selectively sampled into three interleaved datasets $S_1(\mathbf{k})$, $S_2(\mathbf{k})$, and $S_3(\mathbf{k})$, denoted as N (d1, d2, d3), where N is the PE skip size and d1, d2, and d3 are PE shifts. Since only the relative PE shifts are important, with d1=0, d2>d1, and d3>d2, there were a total number of (N-2)(N-1)/2 possible combinations of N(d1,d2,d3). They were all processed by the SPEED algorithm [1] and evaluated for reconstruction quality.

The 2-norm condition number of phasor matrix, P^+P, is defined as the ratio of its largest eigen-value over the smallest, where the superscript "+" represents conjugate-transpose. Large condition number indicates a nearly singular matrix and results in poor SPEED reconstruction. Totally 10 combinations of N(d1, d2, d3) have been found to yield very large condition numbers, and thus should not be used in a practical implementation. They are 6(0, 2, 4), 8(0, 2, 4), 8(0, 2, 6), 8(0, 4, 6), 9(0, 3, 6), 10(0, 2, 4), 10(0, 2, 6), 10(0, 2, 8), 10(0, 4, 6), 10(0, 4, 8), and 10(0, 6, 8).

The reconstruction of general SPEED is similar to that of original SPEED [1], with the following steps: (1) A differential operation was performed on the ghosted maps; 2) Least-square error (LSE) solution and ghost separating steps were applied to generate N separate ghost maps $G_n(\mathbf{r})$, n=0,1,…, N-1; (3) All of the separate ghosts $G_n(\mathbf{r})$ were registered and added together to produce a single deghosted edge map $E_0(\mathbf{r})$; (4) $E_0(\mathbf{r})$ was Fourier transformed into k-space, replacing the k-space center with a few lines of extra true data. Finally, a deghosted image $I_0(\mathbf{r})$ was reconstructed with an inverse Fourier transformation.

The full k-space data were also reconstructed by standard inverse 2DFT into "gold-standard" images for comparison. Reconstruction errors were quantified by using Total Relative Error (TRE) as defined by Eq.(1).

$$TRE = \sqrt{\sum_{x,y}\left[I_0(x,y) - I_g(x,y)\right]^2} \Big/ \sum_{x,y} I_g(x,y) \qquad (1)$$

Results Figures (a-l) present partial results of general SPEED on axial head data, similar results were obtained with data from saggital knee and coronal hip. Fig.(a) is the gold-standard image from full k-space data. Fig.(b) is reconstructed from one of the three interleaved datasets with a direct inverse 2DFT and differential operation, with six-fold ghosting because of the PE skip size N = 6. Fig.(c) is the edge map $E_0(\mathbf{r})$ after deghosted by LSE solution, followed by registration and summation. Fig.(d) is the final deghosted image $I_0(\mathbf{r})$, (e) is a residual map of (d). The TRE of Fig.(d) is (6.72e-4). The sampling combination 6(0, 2, 4) lead to a large condition number, corresponding to strong remaining ghosts in edge map $E_0(\mathbf{r})$, as shown in Fig.(f). Figs.(g)-(l) are final deghosted images with sampling combinations of 4(0, 1, 3), 5(0, 1, 4), 7(0, 2, 3), 8(0, 3, 7), 9(0, 3, 8), and 10(0, 7, 8). Their TRE values are 4.31e-4, 4.44e-4, 6.66e-4, 8.77e-4, 8.45e-4, and 8.95e-4, respectively. These TRE values grow progressively with N as they should be, but all represent a reasonable reconstruction quality.

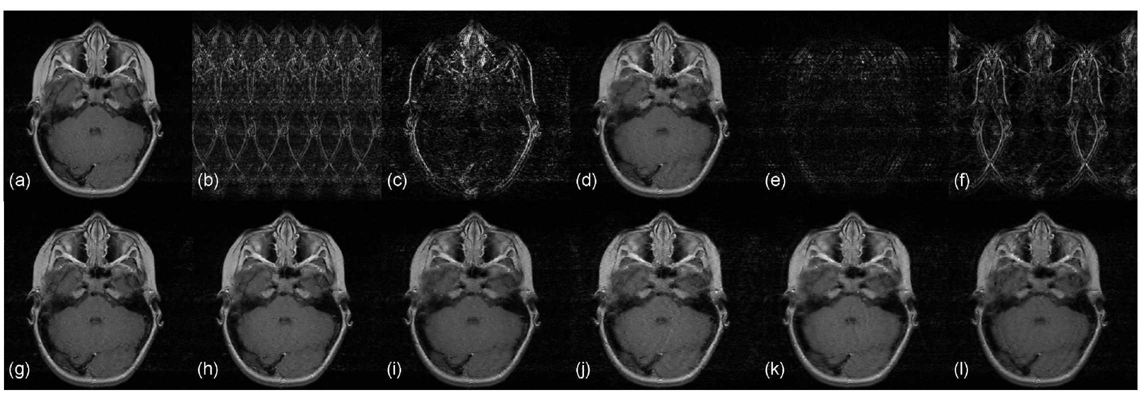

Fig.(a) is the gold-standard image from full k-space data. Fig.(b) is reconstructed from one of the three interleaved datasets with a direct inverse 2DFT and differential operation, with six-fold ghosting due to PE skip size N=6. Fig.(c) is the edge map $E_0(\mathbf{r})$ after deghosted by LSE solution, followed by registration and summation. Fig.(d) is the final deghosted image $I_0(\mathbf{r})$, (e) is residual maps of (d). Fig.(f) has strong remaining ghosts, due to an improper sampling combination 6 (0, 2, 4), also related to a very large condition number. Figs.(g-l) are final deghosted images using sampling combinations 4(0, 1, 3), 5(0, 1, 4), 7(0, 2, 3), 8(0, 3, 7), 9(0, 3, 8), and 10(0, 7, 8), respectively, all with reasonable reconstruction quality.

Discussion It was previously known that when the PE skip size N is a prime number, PE shifts can be selected arbitrarily [1, 4]. However, N does not have to be limited to prime numbers. When N is a composite number, appropriate choice of PE shifts can ensure reconstruction quality. Only a small number of N (d1, d2, d3) combinations were found to result in poor reconstructions, corresponding to strong remaining ghosts and very large condition numbers of the phasor matrices. The more general and flexible sampling schemes offer significantly more freedom in practical implementations and applications of SPEED.

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References [1] Xiang Q-S., Magn Reson Med, 2005;53:1112-7. [2] Pruessmann K.P., et al., Magn Reson Med. 1999;42:952-62. [3] Griswold M.A., et al., Magn Reson Med, 2002;47:1202-10. [4] Chang Z. and Xiang Q-S., Med Phys 2007;34:3173-82.