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, sagittal 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 256x256 in size. The full data were selectively sampled into three interleaved datasets S1(k), S2(k), and S3(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, 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, 6), 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 Gv(r), n=0,1,..., N-1; (3) All of the separate ghosts Gv(r) were registered and added together to produce a single deghosted edge map ED(r); (4) ED(r) was Fourier transformed into k-space, replacing the k-space center with a few lines of extra true data. Finally, a deghosted image I0(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 = ∑ ∫[E0(x,y)−E*(x,y)]^2 / ∫ ∫|E0(x,y)| (1) as defined by Eq.(1).

Results  Figures (a-l) present partial results of general SPEED on axial head data, similar results were obtained with data from sagittal knee and coronal hip. Fig.(a) is the 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 ED(r) after deghosted by LSE solution, followed by registration and summation. Fig.(d) is the final deghosted image I0(r), (e) is a residual map of (d). The TRE of Fig.(d) is (6.72±4). The sampling combination 6(0, 2, 4) lead to a large condition number, corresponding to strong remaining ghosts in edge map ED(r), as shown in Fig.(f). Figs.(g)-(l) are final deghosted images with 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). 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.

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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