Method for Combining UNFOLD with SENSE or SMASH

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Purpose

The purpose of this study was to develop a method for increasing the speed of MR imaging by combining the existing methods of UNFOLD with either SENSE or SMASH.

Introduction

A number of different methods [1-3] have been demonstrated which increase the speed of MR acquisition by decreasing the number of sequential phase encodes. The UNFOLD technique [1] is based on time interleaving of k-space lines and exploits the property that the dynamic or time varying portion of the image is restricted to a fraction of the field of view. The SENSE [2] and SMASH [3] techniques exploit the differences in spatial sensitivity of multiple receiver coils to eliminate the aliased component that results from undersampling.

Theory

The phase of the aliased image components is a linear function of the k-space sampling offset, δk, as illustrated in Figure 1, where the phase of the n-th aliased image is $\phi_n = 2\pi n \delta k/\Delta k$.

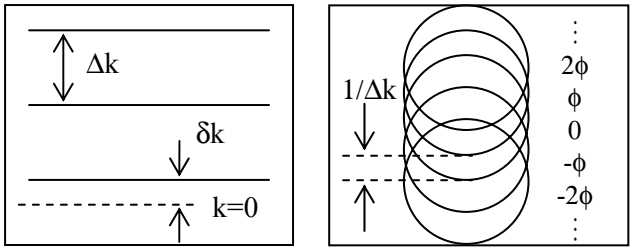

Figure 1. K-space sampling and corresponding point spread function illustrating the phase of aliased components.

The UNFOLD method [1] for 2 fold interleaving uses $\delta k = \Delta k/2$ and sets the sample spacing $\Delta k = 2/FOV$. In this way, the phase of the alias component alternates between 0 and π, thereby alternating the sign of the undesired component. The sequence of reconstructed images (within FOV) may be written as:

$$f(x,y,t) + (-1)^t [f(x, y-FOV/2,t)+ f(x, y+FOV/2,t)] ,$$

where t=0,1,2,… is a discrete time index. If the dynamic region is restricted to the center ½ FOV, then the static top ¼ FOV and bottom ¼ FOV which alias into the center can be eliminated with a temporal low pass filter.

SENSE and SMASH methods may be used to reduce the number of sequential phase encodes by exploiting the spatial information contained in the complex coil sensitivity profiles, $C_k(x,y)$. The SENSE formulation is more general and can be implemented with a wider range of coil profiles and array geometries.

Consider combining UNFOLD with either SENSE or SMASH to achieve a 4x reduction in phase encodes. Choose a phase encode spacing $\Delta k=4/FOV$, and interleave even and odd time frames by shifting phase encodes by $\Delta k/2=2/FOV$. The image reconstructed from the k-th coil will be the sum of aliased images:

$\Sigma_n f(x,y+nFOV/4,t)C_k(x,y+nFOV/4)$, even t

$\Sigma_n f(x,y+nFOV/4,t)C_k(x,y+nFOV/4)(-1)^n$, odd t

The alias components with odd n have alternating sign, therefore these components can be effectively temporally lowpass filtered, provided that the dynamic portion of the image is restricted to the central ¼ FOV. The remaining alias components, $f(x,y\pm FOV/2)$, can be separated using the SENSE method with 2 or more coils, with additional coils increasing the SNR.

For specific arrays, SMASH combines the k-space data from multiple coils to generate an effective linear phase encoding $\exp(i\, 2\pi\delta k\, y)$, thus SMASH can be used to obtain 2 lines of k-space per phase encode, e.g., ky and ky+δk. Choose a phase encode spacing $\Delta k=4/FOV$, a SMASH encoding of $\delta k=1/FOV$, and interleave even and odd shifting by $\Delta k/2=2/FOV$. For this acquisition strategy, the reconstructed image may be written as:

$\Sigma_n f(x,y+nFOV/4,t)\,(1+j^n)$, even t

$\Sigma_n f(x,y+nFOV/4,t)\,(1+j^n)\,(-1)^n$, odd t

The alias images for even n cancel resulting in the image sequence:

$$2\, f(x,y,t) + (-1)^t \Sigma_{n\ odd}\, f(x, y+n\, FOV/4,t)\,(1+j^n)$$

The remaining aliased components can be temporally lowpass filtered provided that the dynamic region is confined to the center ¼ FOV.

In the above, the central ¼ FOV portion will achieve virtually the full temporal resolution, if the remaining FOV is static. This is in contrast with simply using UNFOLD with 4 way interleaving which results in terms (odd n) which have been quarter band translated (j^{nt}), resulting in the sequence of images:

$$\Sigma_{n\ even}\, f(x, y+n\, FOV/4,t)(-1^{nt}) + \Sigma_{n\ odd}\, f(x, y+n\, FOV/4,t)\,(j^{nt})$$

Discussion

We have shown in theory that the UNFOLD method may be combined with either SENSE or SMASH to achieve an overall speed increase of 4:1 (2 from each method). We have shown that the restriction of using the UNFOLD technique combined with either SENSE or SMASH is that the dynamic portion of the field of view must be constrained to the center ¼ of the FOV.

References

1. Madore, B., Glover, G.H., Pelc, N.J. *Magn Reson Med* **42**(5):813-828, 1999.
2. Pruessmann, K.P., Weiger, M., Scheidegger, M.B., Boesiger,P. *Magn Reson Med* **42**(5):952-962, 1999.
3. Sodickson, D.K., Manning, W. *Magn Reson Med* **38**(4):591-603, 1997.