Method for Combining UNFOLD with SENSE or SMASH

Peter Kellman and Elliot R. McVeigh

Laboratory of Cardiac Energetics, National Heart Lung and Blood Institute, Bethesda Maryland 20892 USA

INTRODUCTION

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. The UNFOLD technique [1] is based on time interleaving of k-space lines in sequential images and exploits the property that the outer portion of the field of view is relatively static. 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.

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 highly dynamic portion of the field of view must be constrained to the center ¼ of the FOV.

Results are presented for using combined SENSE and UNFOLD to image the flow in the aorta using phase contrast. A segmented k-space acquisition was used to achieve the desired temporal resolution. By combining SENSE and UNFOLD, the breath-hold was reduced from 40 sec to 10 sec.

METHODS

Theory

The Fourier pair relationship between sampled k-space and image data for the i-th coil may be written as:

$$F_i(k_x, k_y, t) \times (1/\Delta k)\,\mathrm{comb}[(k - \delta k)/\Delta k] \Leftrightarrow f(x,y,t)\, s_i(x,y) * \{\mathrm{comb}(\Delta k\, y)\, e^{-j2\pi\delta k y}\},$$

where the asterisk denotes convolution, $s_i(x,y)$ is the coil sensitivity for coil i, Δk is the sample spacing, and δk is the sampling phase, as illustrated in Fig 1(a).

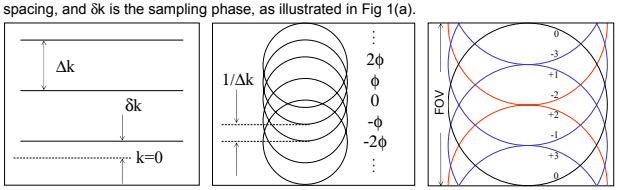

Figure 1. (a) k-space sampling and (b) corresponding point spread function illustrating the phase of aliased components for general case, (c) point spread function for Δk=FOV/4.

The phase of the n-th aliased image, $\phi_n = 2\pi n\delta k/\Delta k$, is a linear function of the k-space sampling offset, δk. The UNFOLD method [1] for R=2 fold interleaving uses δk = Δk/2 and sets the sample spacing Δk = 2/FOV, with FOV defined as the full, unaliased field-of-view. 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:

$$\Sigma_n (-1)^{nt} [f(x, y+nFOV/2, t)\, s_i(x, y+nFOV/2)],$$

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

UNFOLD (R=2) may be combined with SENSE (R=2) to achieve a 4x reduction in phase encodes by choosing a phase encode spacing Δk=4/FOV, and interleave even and odd time frames by shifting phase encodes by Δk/2=2/FOV. The image reconstructed from the i-th coil will be the sum of aliased images:

$$\Sigma_n (-1)^{nt} [f(x, y+nFOV/4, t)\, s_i(x, y+nFOV/4)].$$

The alias components with odd n have alternating sign, therefore these components can be effectively temporally lowpass filtered, provided that the highly dynamic portion of the image is restricted to the central ¼ FOV. The remaining alias components, f(x,y±FOV/2), can be separated using the SENSE method with 2 or more coils, with additional coils increasing the SNR. This specific case is illustrated in Fig 1(c) where the blue aliased images, corresponding to odd n, are rejected using UNFOLD, and the red aliased images, corresponding to even n, are rejected using SENSE.

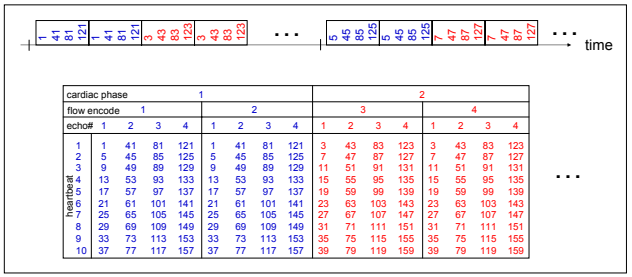

Figure 2. ECG gated, segmented k-space acquisition for phase contrast imaging with combined SENSE and UNFOLD

Table 1 Imaging Parameters

Scanner:	GE Signa 1.5T	Echo Train Length:	4	
Pulse Seq:	Fast Gradient Recalled Echo Train [4]	Bandwidth:	±62.5 kHz	
K-space acq:	ECG Gated, Segmented, Interleaved	TR:	13 msec	
Coils:	4-element cardiac phased array			
FOV:	240x240 mm (192 freq x 160 phase)		# phase encodes acquired:	breath-hold time (sec)
Resolution:	1.25 mm x 1.5mm			
Phase Contrast:	z-axis (thru plane)			
Venc:	150 cm/sec	full k-space	160	40
Flip angle:	15 degrees	UNFOLD	80	20
Slice thickness:	10 mm	SENSE/UNFOLD	40	10

RESULTS

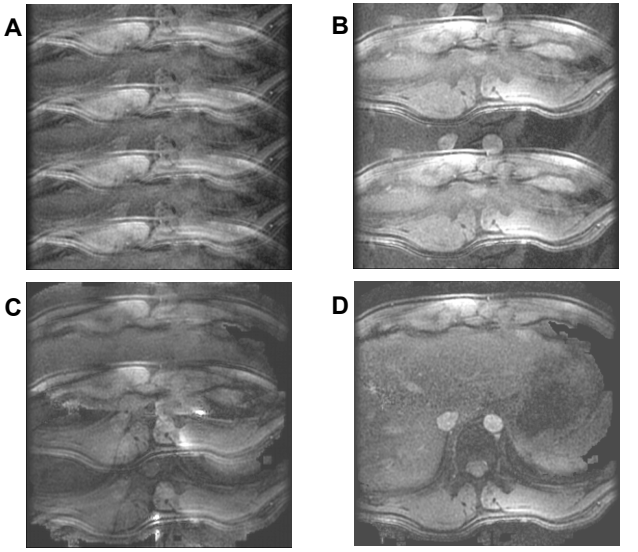

Figure 3. Magnitude Image Reconstructions: (**A**) aliased images without UNFOLD or SENSE (**B**) using UNFOLD temporal filter without SENSE (**C**) using SENSE without UNFOLD) (**D**) using combined SENSE and UNFOLD.

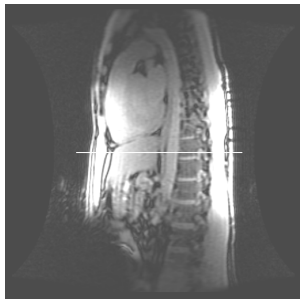

Figure 4. Sagital localizer image showing axial slice location.

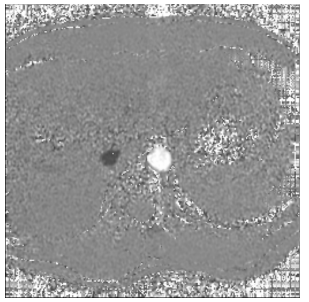

Figure 5. Phase image of axial slice showing aortic flow using combined SENSE and UNFOLD.

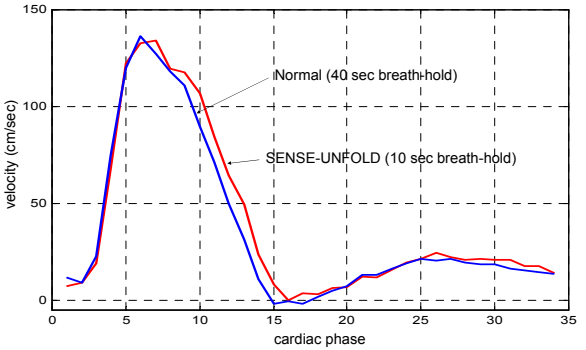

Figure 6. Mean velocity within aorta (axial slice) versus cardiac phase with 26 msec temporal resolution. The breath-hold time was reduced from 40 sec to 10 sec using combined SENSE and UNFOLD.

CONCLUSIONS

- UNFOLD (R=2) and SENSE (R=2) may be combined to achieve overall R=4 rate factor
- Highly dynamic field of view is constrained to central ¼ of unaliased FOV
- Demonstrated combined SENSE and UNFOLD for aortic flow application using gated, segmented k-space acquisition of phase contrast images. Breath-hold time was reduced from 40 sec to 10 sec.

REFERENCES

1. Madore, B, Glover, GH, Pelc, NJ. *Magn Reson Med* **42**(5):813-828, 1999.
2. Pruessmann, KP, Weiger, M, Scheidegger, MB. Boesiger, P. *Magn Reson Med* **42**(5):952-962, 1999.
3. Sodickson, DK, Manning, W. *Magn Reson Med* **38**(4):591-603, 1997.
4. Epstein, FH, Wolff, SD, Arai AE. *Magn Reson Med* **41**(3):609-613, 1999.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Fredrick Epstein for his assistance in imaging and pulse sequence design.