The UNFOLD strategy can help parallel imaging

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Introduction:

Originally presented as a stand-alone method for fast imaging, UNFOLD [1] seems to have found an important niche as a helper to parallel imaging. Three main methods, by three different groups, have been published on the topic of combining UNFOLD and parallel imaging: TSENSE [2], our UNFOLD-SENSE [3,4], and *k-t* SENSE [5]. Based on the successes reported with all three approaches, the value of UNFOLD as a helper to dynamic parallel imaging now seems reasonably well established.

Each one of the three existing hybrid methods has its strengths: Kellman *et al.* introduced the clever idea that UNFOLD can be used for self-referencing purposes, we showed how UNFOLD and parallel imaging can be fused to achieve optimum performance from both, and Tsao *et al.* showed how information from a separate training scan can be included in the reconstruction. This presentation consists of three parts: 1) A review of the UNFOLD strategy, 2) A short description of our own UNFOLD-SENSE approach, and 3) A look at a few questions not yet properly addressed by the existing hybrid methods.

1) The UNFOLD strategy

As shown in Ref. [1], applying a (time dependent) k_y shift $f(t)$ to the sampling function causes aliased signals to be modulated by a function:

$$D(t) = \exp(i2\pi f(t)j), \qquad [1]$$

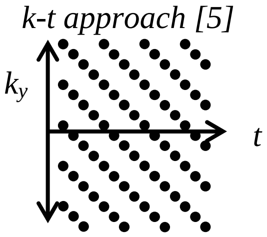
where j is the order of a given layer of aliasing (j=0 for non-aliased signal), and $f(t)$ is expressed as a fraction of the increment between k_y lines.

In other words, one can control the phase of aliased signals by shifting the sampling function along k_y from time frame to time frame. All applications of UNFOLD to date, including TSENSE and *k-t* SENSE, use the special case:

$$f(t) = mt, \qquad [2]$$

where t is the time-frame number and m is a proportionality constant, i.e., a slope. The appeal of this special case is that it makes $D(t)$ in Eq. 1 a Fourier function. As a consequence, UNFOLD's effect in the Fourier domain becomes very simple: it displaces aliased signals along the temporal frequency axis.

UNFOLD's sampling strategy [1] involves shifting the sampling function along k_y by a fixed increment from frame to frame (Eq. 2). In *k-t* SENSE, an identical strategy is used and is referred to as sampling on a "sheared grid in *k-t* space". One advantage of this terminology is that it makes an explicit link with a very good paper by Xiang and Henkelman on *k-t* space [6]. The sampled data is Fourier transformed in all directions to yield a temporal frequency spectrum at each spatial location. This *x-y*-frequency block of data has too many dimensions to be easily visualized: For display purposes, one can show the frequency content at selected pixel locations using 1D plots [1-4], or use 2D grayscale plots as in *k-t* SENSE to show the frequency content of all *y* locations at a given *x* [5].



Sampling on a "sheared grid in k-t space" (k-t approach)

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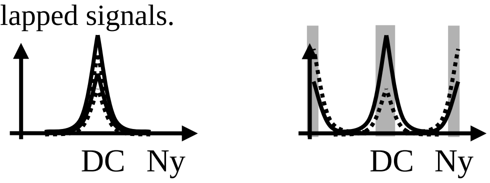
sampling function shifted by a fixed increment from frame to frame" (UNFOLD)

UNFOLD is a simple tool to displace aliased signals along a temporal-frequency axis. The distance between k-space lines (FOV) determines what spatial locations overlap together, and m in Eq. 2 (the increment from frame to frame) determines the size of the displacements applied along the frequency axis.

2) Short description of UNFOLD-SENSE

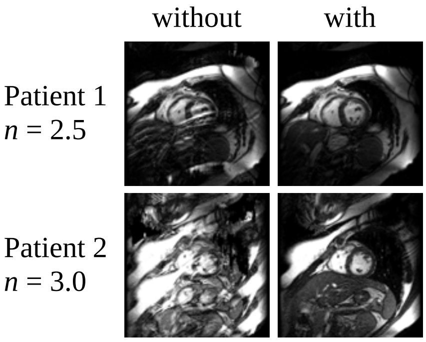
Suppose an acceleration factor of n=4. Up to four spectra overlap in the temporal frequency domain, at any given pixel location. It is mathematically equivalent to apply parallel imaging one time point at a time (as usual), or one frequency point at a time (as done here). Parallel imaging, with an acceleration factor of 4, could be used to separate the four overlapped signals.



UNFOLD displaces half of the spectra to Nyquist, creating regions of reduced overlap (shown shaded)

UNFOLD's purpose is to move spectra in the temporal frequency domain. With m=0.5 in Eq. 2, it can move half of the spectra all the way to Nyquist. If one assumes that at Nyquist, the decaying tails of the DC-bound spectra are negligible compared to the central parts of the Ny-bound spectra, then only 2 signals instead of 4 overlap near Nyquist. A similar situation arises near DC. In narrow regions near

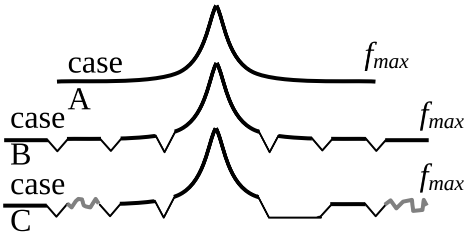
DC and Nyquist, shown shaded in the figure above, an acceleration factor twice smaller can be used since only half of the signals are present. UNFOLD allows these sensitive regions, which typically contain most of the energy in the bandwidth, to be treated with a more reliable algorithm featuring a smaller acceleration factor. Allowing these sensitive regions to be treated with a more reliable algorithm (acceleration of 2 instead of 4 here) leads to significant artifact suppression [3,4]. The approach also works in suppressing amplified noise.



Results from two patients, without and with the UNFOLD artifact suppression. A 4-coil cardiac array was used, and accelerations of 2.5 and 3.0 were obtained. The method is self-calibrated.

In addition to the UNFOLD-based artifact suppression [3], UNFOLD-SENSE [4] also includes a self-calibration scheme that is a modified version of the one in TSENSE [2], and a reconstruction algorithm featuring the same simplicity and processing speed as Cartesian SENSE while able to handle some degree of variation in sampling density along the phase-encoding direction.

3) A few remaining questions



- What does "temporal resolution" really mean?

Temporal resolution is given by the inverse of the highest frequency resolved, $1/f_{max}$ (case A above). But what if there are holes in the bandwidth, as in case B? Does case B truly has better temporal resolution than case A, as its higher f_{max} suggests? The problem can be compounded by larger holes, and regions reconstructed with less accuracy (case C). It is relatively easy with UNFOLD to generate large bandwidths, with a large f_{max}. Reconstruction accuracy over a large bandwidth is, of course, a more stringent goal. To compare implementations featuring different frequency responses, a temporal equivalent of the modulation transfer function (MTF) approach could presumably prove useful.

- What is a good way to fail?

Parallel imaging involves acquiring data corrupted by aliasing artifacts, and then correcting these artifacts. When the method is pushed too far and fails, significant levels of aliasing artifacts may remain. The UNFOLD artifact suppression can increase the acceleration at which failure occurs, but left-over artifacts remain the main sign something went wrong. By enforcing a resemblance between the results and a low-resolution training scan, *k-t* SENSE resists the creation of such artifacts. Its failure mode is more subtle, a feature that may or may not prove to be a strength.

- Should all pixels be treated equal?

The image on the left contains only random noise. Because different time filters were used for different spatial locations, the SNR varied spatially and features that did not exist in the original data appeared, carved into the noise. To avoid creating artificial features, UNFOLD-SENSE applies the same temporal filters to all pixels. In a quest for speed, *k-t* SENSE allows the temporal processing to change from pixel to pixel. Between the more cautious approach of UNFOLD-SENSE and the more aggressive approach of *k-t* SENSE, a series of potential compromises may well be found.

Conclusion: In dynamic imaging, UNFOLD proves to be a very worthwhile addition to parallel imaging.

References:

[1] Madore , Glover, Pelc. MRM 42:813 (1999).
[2] Kellman, Epstein, McVeigh. MRM 45:846 (2001).
[3] Madore. MRM 48:493 (2002).
[4] Madore. MRM 52:310 (2004).
[5] Tsao, Boesiger, Pruessmann. MRM 50:1031 (2003).
[6] Xiang, Henkelman. MRM 29:422 (1993).

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