k-t SENSE for efficient dynamic parallel imaging by joint space-time consideration

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INTRODUCTION:

The general principles of parallel imaging [1-3] have been well established. However, two issues remain, suggesting that there may be room for further improvement. These concern background voxels and signal-to-noise-ratio (SNR) efficiency.

1. Background voxels

As described in ref. [2], reconstruction is improved by identifying background voxels. This is expected from the finite-support principle [4-6]. Since background voxels contain no signals, they can be eliminated from consideration, so the number of unknowns in the reconstruction equation can be reduced. However, this binary classification (i.e. background / non-background) is somewhat artificial, as it does not take into account partial volume effects. i.e. part of a voxel may contain background, while the remaining portion may be non-background. Moreover, it seems reasonable to expect that other post-acquisition criteria may also benefit reconstruction besides background voxels.

2. SNR efficiency

It is well known that the raw data in MRI can be acquired with an infinite number of trajectories [7]. Parallel imaging further adds to the diversity by using coil sensitivities as a complementary encoding mechanism. However, SNR degrades with higher acceleration factor, due to the non-orthogonality of coil encoding. Thus, if we have a static object and a fixed amount of scan time, we can either acquire a fully sampled image without acceleration, or *N* images at *N*-fold acceleration followed by averaging. Even though the scan time is identical in both cases, the SNR efficiency is lower in the second case. What is gained at the expense of reduced SNR efficiency is robustness, in case the object does not remain static during the entire acquisition. However, as before, this binary static / non-static classification is somewhat artificial, and there may be better approaches to handle cases in-between.

These shortcomings have prompted several recent developments that focus on exploiting spatiotemporal correlations [8-10]. One such method, *k-t* SENSE [10], extends the concept of parallel imaging by considering data acquisition in both *k*-space and time in a joint fashion. By treating the spatial and temporal axes on an equal footing, SNR efficiency can be adjusted in a more flexible fashion. Moreover, predictability in temporal variation, which translates to reduced degrees of freedom, can be used to benefit reconstruction in the same fashion as background voxels. Finally, the *k-t* approach utilizes a regularization approach that replaces the hard binary decision used in the background voxel selection by a soft decision that minimizes the expected error. In this fashion, it is possible to achieve excellent image quality at high acceleration that even exceeds the number of receiver coils.

THEORY:

The *k-t* approach makes use of the observation that the signals in a natural image series can be compressed into a more compact format in *x-f* space. *x* and *f* represent spatial coordinates and temporal frequencies, respectively. As a simple example, suppose we acquire two time frames (A and B), and we perform an addition and a subtraction between the time frames (i.e. A+B, and A-B). This is equivalent to a two-point Fourier transform. If the imaged object is entirely static, the summed image (i.e. A+B) would contain all the signals, while the difference image (i.e. A-B) would contain only noise. Thus, the signals from 2 images have been compressed into a single image (i.e. the summed image), while the difference image effectively contains only "background voxels". In the more general case, if there are *N* time frames, we can similarly perform a transformation along the time axis. If the basis functions used in the transformation match the time variation of the images well, the signals will be compressed into a small number of motion components, while the remaining components contain mostly background voxels. The compression of information is illustrated in Fig. 1 for a time series of short-axis anatomical images of the heart. The middle panel shows the signal intensities for one pixel column at different time points. This representation is termed *x-t* space, where *t* denotes time. Applying an inverse Fourier transform along *t* yields the *x-f* space representation on the right. With this transformation, the signals, which are distributed in *x-t* space, are now concentrated in localized regions in *x-f* space.

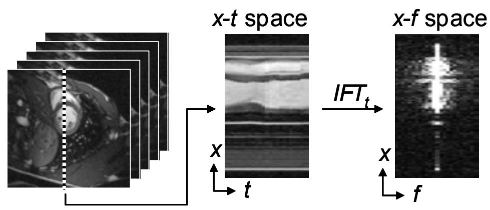


Fig. 1. *Left to right: a cine series of short-axis images; x-t space representation showing one pixel column at different time points (i.e. cardiac phases); x-f space representation showing one pixel column at different temporal frequencies.*

The scan can be accelerated by skipping lines in *k*-space at different time points *t*. This is equivalent to undersampling a higher-dimensional *k-t* space. According to the principles of the Fourier transform, if *k-t* space is uniformly undersampled, the signals in *x-f* space will be replicated (i.e. aliased), leading to potential signal overlap (Fig. 2). This aliasing makes it possible to utilize the relatively empty portions of *x-f* space. However, if left untreated, it also leads to back-folding artifacts. One solution to overcoming these artifacts is to set voxels that are known to be background to zero. However, the effectiveness of this strategy is rather limited, because the signal compression may only be partial. i.e. the signals are only concentrated but not completely confined to limited regions in *x-f* space. In the *k-t* approach, this binary decision is replaced by a soft decision using a regularization scheme that compares the amount of expected signals with the noise level. The reconstruction formula implicitly balances the errors from residual aliasing and those from amplified noise, such that the overall expected least-squares error is minimized [10]. The expected error from residual aliasing is estimated from training images. The training images have a full temporal resolution, but a low spatial resolution, so they can be acquired in a very short period.

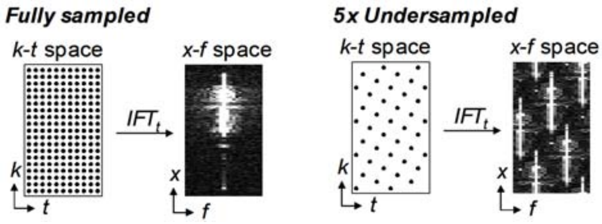


Fig. 2. *Left: fully sampled k-t space leads to a fully resolved x-f space. Right: uniform undersampling of k-t space leads to aliasing (i.e. signal replication) in x-f space, leading to potential signal overlap, which is then resolved by k-t reconstruction.*

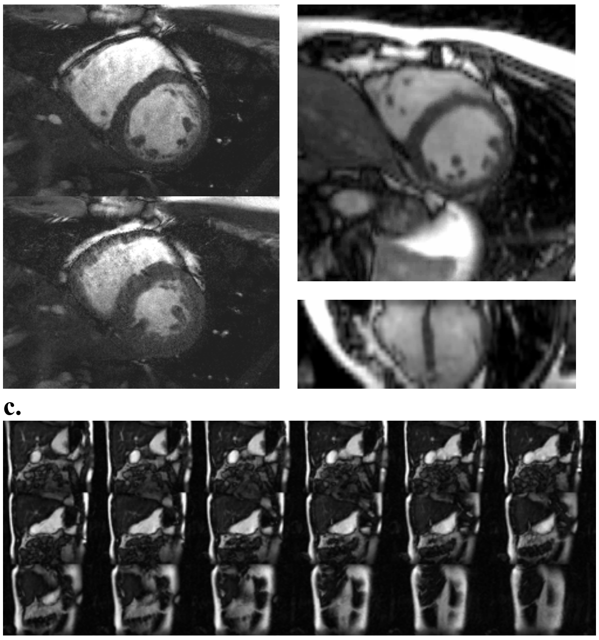
RESULTS:

Fig. 4 shows a number of exemplary results acquired with either a 5- or 6-element phased array using *k-t* SENSE. Fig. 4a shows high-resolution 8x accelerated 2D breath-held cine images at diastole (top) and systole (bottom) with an in-plane resolution of 0.8x0.8mm^2 acquired in ~12 seconds. Fig. 4b shows 3D 5x accelerated breath-held cine images in short axis view (top) and reformatted 4-chamber view (bottom) with a voxel resolution of 2x2x5mm^3 acquired in 21 seconds. Fig. 4c shows real-time 3D 8x accelerated gastrointestinal images with a voxel resolution of 2x2x5mm^3 at ~1 frame/second.

DISCUSSION:

The capabilities of parallel imaging can be further extended by considering time as a sampling axis in the same fashion as for the phase-encoding axes. In this way, acquisition in space and in time can be balanced to make better use of acquisition time. An important aspect of the *k-t* approach is the way it utilizes training data to minimize the expected reconstruction error. In this fashion, it is unnecessary to make assumptions about the signal distribution, and at the same time, it does not over-constrain the reconstruction, unlike many of the previous prior-information-driven methods [6]. One cautionary note is that if the acceleration is increased excessively, the signals will be packed too densely in *x-f* space, and the reconstruction may not be able to resolve the aliasing completely [10]. In that case, they may be residual aliasing or temporal blurring, depending on whether too much or too little signals are assigned to a reconstructed *x-f* voxel, respectively. Nevertheless, this situation can be alleviated or avoided by using lower acceleration factors, or by using more localized receiver coils to further leverage the capability of parallel imaging. In general, the *k-t* approach permits significant acceleration in a variety of MR measurements, and up to 8-fold acceleration is demonstrated here. This degree of acceleration not only makes common scans more practical; it also brings more sophisticated measurements towards a clinically relevant realm.

a. **b.**



c.

Fig. 4. Examples of *k-t* SENSE images for (a) high-resolution (0.8x0.8mm^2) 2D cine at 8x acceleration, (b) 3D whole-heart cine at 5x acceleration, and (c) 3D real-time gastrointestinal imaging at 8x acceleration.

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