TIME-RESOLVED PARALLEL IMAGING WITH A REDUCED DYNAMIC FIELD OF VIEW

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ABSTRACT

This paper introduces a novel method for accelerated dynamic image acquisition for cardiac MRI. This method combines two different formalisms for reconstruction from sparse data by incorporation of prior information. Parallel imaging uses information about coil geometry in imaging systems with multiple receiver coils. Reduced field of view (rFOV) imaging exploits knowledge about static regions in a dynamic image scene. The novel method combines the SPACE-RIP implementation of parallel imaging with the Noquist rFOV imaging method, which both use a direct inversion model for image reconstruction. The theory is presented for integrated application of these methods, and results are presented of supporting experiments with simulated and real MRI data, retrospectively subsampled to generate sparse data sets. Successful application of the method confirms multiplicative combined acceleration.

Index Terms— MRI, parallel imaging, SPACE-RIP, rFOV, Noquist

1. INTRODUCTION

MRI provides clinically relevant anatomic and functional information noninvasively and with minimal risk. Imaging speed is very important in dynamic MR imaging applications such as cardiac imaging. Fast imaging allows prevention of respiratory motion artifacts by breath-held acquisition. Patient safety considerations preclude use of faster gradient switching or higher RF power to speed up the pulse sequence.

Removal of data redundancy by incorporation of prior information about the image is currently investigated in several ways. Parallel imaging [1–5] exploits spatial redundancy in signals from multi-channel receiver systems using receiver coil sensitivity maps. Spatiotemporal redundancy may be exploited in dynamic imaging if parts of the field of view (FOV) do not change much over time [6–8]. Ideally such separate and independent sources of data redundancy may be exploited jointly for combined gains in imaging speed. Both types of methods may operate either in the image domain following Fourier inversion of the raw k-space data, or operate in the k-space domain. This distinction determines a priori compatibility for combined implementation of any of these methods for parallel imaging and spatiotemporal correlation. Methods which strictly use temporal filtering (like UNFOLD [6]) may be compatible with either approach.

In this paper we present such a hybrid imaging acceleration method, which combines the SPACE-RIP and Noquist methods to incorporate prior information both from a reduced dynamic FOV and receiver coil sensitivity maps. The method was named “No’nSENSE” – until successful results were obtained. The method uses a direct (pseudo-)inversion approach for reconstruction and combines specific advantages of both methods, setting it apart from alternative approaches [7, 9, 10]: full preservation of spatial and temporal resolution compared to conventional acquisition of a full k-space grid and great flexibility with respect to k-space view selection towards SNR or other relevant optimization. The paper is organized as follows. In the next section we introduce the principle of No’nSENSE method and provide details of experimental methods. This is followed by first experimental results with No’nSENSE on simulation phantom data and retrospectively full-grid MRI image data, and a comparison with results of applying SENSE, SPACE-RIP, or Noquist alone. We close with a discussion of the results and conclusions.

2. MATERIALS AND METHODS

Parallel Imaging: At a Nyquist sampling rate, conventional acquisition grids have sufficiently fine sample spacing to avoid harmful foldover artifacts in DFT reconstruction. Redundancy in the image data in parallel imaging stems from the availability of multiple RF receiver channels, where each RF coil measures the same signal with a different coil sensitivity encoding. This redundancy is removed by lowering the sampling rate, thus reducing the scan time. The image is reconstructed from these sparse data, assisted by a model of the modulation of the image function f into acquired k-space data by a known sensitivity profile Sc for each coil.

Frequency encoding reconstruction is performed by conventional DFT beforehand, and will not need further consideration in the following. For any given frequency encoding pixel, the data samples F(k) in phase encoding direction can
be expressed as a Fourier transform of \( f(x) \), weighted by the coil sensitivity \( S_c(x) \). It can be written as

\[
F_c(k) = \sum_{n=1}^{N} S_c(n) f(n) e^{i 2\pi kn}. \tag{1}
\]

In matrix notation, for all \( C \) coils combined:

\[
\begin{bmatrix}
F_1(k) \\
F_2(k) \\
\vdots \\
F_C(k)
\end{bmatrix} = 
\begin{bmatrix}
S_1(1) e^{i 2\pi k 1} & \cdots & S_1(N) e^{i 2\pi k N} \\
S_2(1) e^{i 2\pi k 1} & \cdots & S_2(N) e^{i 2\pi k N} \\
\vdots & \ddots & \vdots \\
S_C(1) e^{i 2\pi k 1} & \cdots & S_C(N) e^{i 2\pi k N}
\end{bmatrix}
\begin{bmatrix}
f(1) \\
f(2) \\
\vdots \\
f(N)
\end{bmatrix} \tag{2}
\]

Or:

\[
F = M_{\text{parallel}} f \tag{3}
\]

The SPACE-RIP parallel imaging method: The image reconstruction by the SPACE-RIP method is simply a direct inversion of this weighted Fourier transform matrix, combined for all coils:

\[
f = M_{\text{parallel}}^{-1} F \tag{4}
\]

“Noquist” Reduced field of view (rFOV) imaging: Another approach to achieve accelerated imaging is to exploit prior knowledge about static portions of the FOV [6–8], sometimes called “reduced field of view” (rFOV) imaging. Noquist is a rFOV method which is based on a direct inversion model. Again, frequency encoding is performed conventionally and not considered here. Phase encoding data \( F(k, t) \) for a dynamic image sequence \( f(x, t) \) can be expressed as:

\[
F(k, t) = \sum_{n=1}^{N} f(n, t) e^{i 2\pi kn}. \tag{5}
\]

With Fourier coefficients represented in matrix \( M \), conventional image reconstruction for each time point or “frame” \( t \) would be

\[
f(x, t) = M^{-1} F(k, t). \tag{6}
\]

Consider a cine image sequence with \( N \) phase encodings per time frame. Since the outer portion of FOV from each time frame is static, we only need to reconstruct it once for the entire sequence. If we define the phase encoding sizes of the static and dynamic portions of the FOV as \( N_s \) and \( N_d \), then \( N = N_s + N_d \). Hence, the image \( f \) in a single frame can be partitioned as \( f = \begin{bmatrix} f_s^T & f_d^T \end{bmatrix}^T \). The corresponding Fourier transform matrix is similarly partitioned as \( M = \begin{bmatrix} M_s & M_d \end{bmatrix} \).

For a dynamic sequence with \( T \) time frames, the data \( F_t \) of all frames \( t \) may again be combined into a single vector:

\[
\begin{bmatrix}
F_0 \\
F_1 \\
\vdots \\
F_{T-1}
\end{bmatrix} = 
\begin{bmatrix}
M_s & M_d & 0 & \cdots & 0 \\
M_s & 0 & M_d & \cdots & 0 \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
M_s & 0 & 0 & \cdots & M_d
\end{bmatrix}
\begin{bmatrix}
f_s \\
f_{0,D} \\
f_1,D \\
\vdots \\
f_{T-1,D}
\end{bmatrix} \tag{7}
\]

Or:

\[
f = M_{\text{noquist}}^{-1} F \tag{8}
\]

\[
\text{Fig. 1. Comparison of sampling schemes}
\]

Integrated parallel/rFOV Imaging: We observe that \( M_{\text{parallel}} \) and \( M_{\text{noquist}} \) have similar formulations. To implement accelerated imaging using both sources of prior knowledge, these two model formulations may be combined naturally into the “No’nSENSE” method. In equation Eq. 9 we have combined Eq. 2 and Eq. 7, where the measured data \( F_t,c \) are now indexed by time frame \( t \) as well as by coil \( c \).

Scan acceleration factors: We define \( N \) as the number of conventional phase encodings, and \( N_{\text{sample}} \) as reduced the number of phase encoding samples. \( C \) is the number of coils. \( T \) is the number of time frames.

For the SPACE-RIP method, the minimum \( N_{\text{sample}} = N/C \).

Since in Noquist the static part is only reconstructed once, we need, for a fully determined system in each frame,

\[
N_{\text{sample}} = N_s/T + N_d. \tag{10}
\]

For No’nSENSE, the minimum \( N_{\text{sample}} \) for each frame would be reduced further to

\[
N_{\text{sample}} = N_s/(RT) + N_d/R. \tag{11}
\]

The data reduction factor for fast imaging is \( R = N/N_{\text{sample}} \). Parallel reduction factor \( R_p \) is up to number of coils. rFOV reduction factor \( R_{\text{noq}} \) up to \( FOV/FOV_{\text{dyn}} \). No’nSENSE combines multiplicatively the acceleration from both parallel and Noquist \( R = R_p \times R_{\text{noq}} \). Figure 1 illustrates how individual sampling schemes for both methods are combined in a straightforward manner. The example has 16 phase-encodings and 4 frames.

3. EXPERIMENTS AND RESULTS

We implemented and tested the No’nSENSE method in MATLAB. Reconstructions are performed on phantom data and real MRI data. We also implemented the SPACE-RIP and Noquist methods individually for comparison.

Phantom data: Phantom data have 128 simulated frequency and phase encodings, 16 frames, and 4 coils. The
Fig. 2. Phantom data results. The figures show frame 1 of 16 from a ciné sequence with various types of simulated motion.

sensitivity maps were calculated by the Biot-Savart law. Figure 2 shows phantom data experimental results. We used reduction factor $R_p = 4$ for SPACE-RIP and Noquist reduction factor $R_{nq} = 1.88$ for 16 frames and 50% dynamic FOV, thus with combined No'nSENSE reduction factor is $R = 7.53$.

Real data: MRI data were acquired on a 1.5 Tesla Philips scanner. It is a breath-hold cardiac ciné image with 232 phase encoding and 512 frequency encoding samples, 20 time frames, and has data from five receiver coils. Each coil image was divided by the square rooted sum of squares of all coil images to obtain the sensitivity maps. For data selection we extended the patterns of Figure 1.

Due to geometric correlation between coils, the maximum SPACE-RIP acceleration factor 5 may be expected to yield unstable inversion results. Figure 3 shows the reconstruction results for reduction factor $R_p = 2$ for SPACE-RIP and 50% dynamic FOV for Noquist. The conventional, SPACE-RIP, Noquist, and No’nSENSE reconstructions used 232, 116, 122, and 61 phase encodings per frame respectively, corresponding with reduction factors 1, 2, 1.9, and 3.8. Figure 4 shows the full grid results for time frames 1, 2, 19, 20 of the series.

No’nSENSE does not use interpolation so it preserves full spatiotemporal resolution. Non’SENSE allows multiplication of the individual acceleration factors through combination of the SPACE-RIP and Noquist methods, at a corresponding cost in multiplicatively accumulated SNR penalty factors. Table 1 demonstrates the noise amplification factor of region (bigger) and 2(smaller) compared to different methods for phantom images (see fig 2(a)). No’nSENSE involves inversion of multiple large matrices (size $T \times C \times N_{sample}$), which makes the computational cost of the method higher than that of Noquist or parallel imaging methods alone.

<table>
<thead>
<tr>
<th>Region</th>
<th>Convention ($R_p = 4$)</th>
<th>SPACE-RIP ($R_{na} = 1.8$)</th>
<th>Noquist ($R = 1.6$)</th>
<th>No’nSENSE ($R = 7.53$)</th>
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<tr>
<td>1</td>
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6. REFERENCES


