Integrated Parallel Imaging and rFOV Without Temporal Filtering

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Introduction

Parallel imaging methods like SENSE[1] exploit data redundancy in imaging with multiple receiver coils to reduce the data requirements, by incorporating knowledge about receiver coil sensitivity. Reduced field of view (rFOV) methods like Noquist[2] similarly exploit redundancy in ciné/dynamic imaging due to the presence of static regions in the FOV. These sources of prior information are in principle independent, and may thus be combined for cumulative scan time reduction. The *kt*-SENSE method[3] combines SENSE and rFOV through spatio-temporal interpolation, expanding on the UNFOLD model[4]. We are investigating an approach without temporal filtering, thus preserving temporal resolution, to combine SENSE and Noquist. On a cartesian sampling grid in *k*-space, both SENSE and Noquist are commonly implemented in the phase encoding dimension(s) only.

<u>Noquist</u>: For a ciné image sequence with T independent frames and a FOV with N_S static and N_D dynamic points, Noquist models the *(k,t)*-space data F for entire dynamic image simultaneously by a single matrix M, which contains the Fourier model coefficients: $F=Mf$. The image reconstruction is represented by the inverse of this matrix: $f=M^{-1}F$. For conventional ciné imaging f is simply a concatenation of the individual frame images, resulting in a block-diagonal matrix M with identical blocks of Fourier coefficients for each image of the sequence, and M^{-1} contains identical blocks of inverse Fourier coefficients. Noquist reduces this model by representing the static part of the FOV only once in the entire sequence, since it is identical in all frames. The total size of the ciné image is thus reduced from $T(N_S+N_D)$ to N_S+TN_D. This propagates into accordingly reduced size requirements for each of the equally-sized temporal *k*-space sample vectors F for each time point to N_D+N_S/T. Selection of a subset of *k*-space views in each frame is constrained by the requirement to keep matrix M invertible.

<u>SENSE</u>: An image f is observed by a receiver coil c with sensitivity S_c as the product $f_c=f.S_c$, with corresponding Fourier data $F_c=Mf_c$. With complete prior knowledge of S_c at all image locations for each of C independent receiver coils, complete conventional sampling of F_c yields C-fold redundant data. Accordingly, reduction of the number of acquired k-space views by a factor R up to C may present a feasible image reconstruction problem. Recovery of f from the reduced Fourier data sets F_c, simultaneously acquired from all C coils, may be achieved through different strategies, with different constraints in flexibility in sampling patterns and computational complexity.

Materials and Methods

Both the SENSE and the Noquist methods can be implemented using a direct-inversion implementation. This approach was followed in our earlier Noquist research[2], and was again employed here for combination of the methods. For over-determined systems (SENSE factor $R<C$) a pseudo-inverse matrix was applied for reconstruction. Again, only data reduction in phase encoding direction was implemented. Readout reconstruction is done by conventional DFT. Since coil sensitivity maps vary across the readout axis, readout reconstruction must precede phase encoding inversion, and phase encoding inversion was calculated separately for each readout location. Selection of phase encoding view subsets was done by first sub-sampling at rate R at regular intervals, then further reducing the pattern resulting following the scheme proposed for Noquist[2].

A prototype reconstruction procedure was implemented in MATLAB 7 on a 3 GHz dual-core PC running 64-bit Linux. Reconstructions were performed for simulation phantom data, which mimic different types of cyclic dynamics, including translational and contractile motion, and intensity changes at static locations, with all dynamic regions within the central half of the FOV (Figs. 1 and 2). Sensitivity maps were synthesized, governed by the Biot-Savart law, of 4 simulated circular coils orthogonal to the image plane, located near the FOV boundaries (Fig. 3). We reconstructed for SENSE reduction factors 2 to 4, different coil radii, and various static and dynamic FOV proportions. Noise amplification metrics were computed from the reconstruction matrices as outlined in (2).

Results

Our experiments confirm theoretic expectations that combining SENSE and Noquist requires the acquisition of only $N_S/(RT)+N_D/R$ lines per frame/coil, with N_S, N_D and T defined as introduced above, and R the SENSE reduction factor ($1\leq R\leq C$). The overall acquisition time reduction factor multiplies the acceleration factor of the individual methods. For 50% dynamic FOV, SENSE factors $R=2$ (Fig. 4) and $R=3$ give good results free of artifacts, with reduction factors of 3.76 and 5.66. In these cases with stable reconstructions the combined noise amplification approximately follows multiplication of the noise factors of the individual methods: from 5.6 (SENSE,$R=2$) or 20.6 (SENSE,$R=3$) and 1.6 (Noquist, 50% dynamic FOV) we obtain 8.8 and 34 for the new method (mean values).

When the maximum SENSE factor $R=C=4$ was used, with cumulative reduction factor 7.52, reconstruction artifacts are observed, most prominent in the dynamic part of the image (Fig. 5, arrows). These coincide with ill-conditioned reconstruction matrices, also present for SENSE reconstruction in these situations without Noquist. These observations are consistent with literature reports on noise propagation in SENSE[5], and are possibly related to high levels of similarity among coil sensitivity maps at these locations. Noise amplification exceeds in some situations the expected multiplicatively combined individual factors.

Discussion and Conclusions

Combining prior information from a reduced dynamic field of view and coil sensitivity maps is feasible for ciné MRI. Combination of SENSE and Noquist methods allows multiplication of the individual scan acceleration factors within a stable range, at a cost of similarly accumulated SNR penalties. Computational cost is approximately an order of magnitude higher than that of Noquist alone. Optimized coil geometry and more robust and efficient reconstruction may provide further improvement in achievable cumulative acceleration.

Figure 1: Left coil image in "diastole"

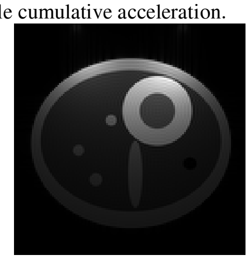

Figure 2: Top coil image in "systole"

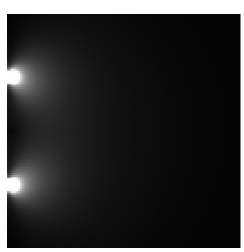

Figure 3: Left coil sensitivity map

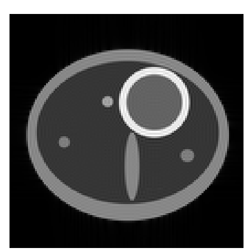

Figure 4: R=2, Noquist 50% static FOV

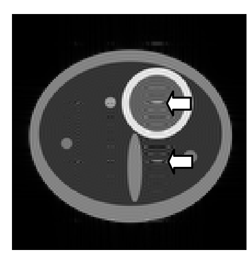

Figure 5: R=C=4, Noquist 50% static FOV

References

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