Parallel Cardiac CINE Imaging: Application to "Dixon" Water-Fat Separation and Steady-State Free Precession

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Introduction: Balanced steady-state free precession (SSFP) is a rapid, short TR imaging technique well suited for cardiac imaging because of its high SNR and excellent blood-myocardial contrast (1,2). However, SSFP is limited by the fact that water and fat both appear bright and are difficult to distinguish, possibly obscuring underlying pathology. A recently described three-point "Dixon" water-fat separation technique has been applied to multi-coil cardiac SSFP CINE imaging to generate separate water and fat CINE images (3). Unfortunately, the decomposition of water from fat requires a three-fold increase in the minimum scan time, compared to conventional SSFP CINE imaging. This increase in the minimum required data limits the achievable spatial and temporal resolution of this method. Despite the increase in minimum imaging time, this water-fat decomposition method is SNR efficient with an effective number of signal averages close to three (3).

Parallel imaging methods (4,5,6) exploit differences in the spatial sensivity profiles of multiple receiver coils to resolve aliasing ambiguities that occur when the object size exceeds the phase encoding field of view. This permits decreases in the the density of k_y lines to "accelerate" the data acquisition by reducing the minimum required data sets by factors that are less than or equal to the number of coil elements, typically 2-4. The purpose of this work was to apply parallel imaging techniques to reduce the required minimum amount of data needed to decompose fat from water, in order to improve spatial and temporal resolution of this approach to the level that are comparable to conventional SSFP CINE acquisitions.

Theory: We have recently described an iterative least-squares water-fat separation method that uses a generalized algorithm to decompose water and fat multi-coil images acquired at short echo times (3). This facilitates the acquisition of separate water and fat SSFP images with short TRs and minimal banding artifacts, and has been applied successfully to CINE acquisitions. In this work, we selected a TE increment of 0.9ms at 1.5T as a good compromise between maximizing SNR performance of the water-fat decomposition, and minimizing banding artifacts by maintaining a TR of 5ms or less.

"Unwrapping" of under-sampled data obtained with the three-point method, as part of a parallel MRI acquisition must be performed for each of the three images acquired at different echo times. The reconstruction of full field of view (FOV) images must accurately preserve the phase of the three complex images, which is necessary for accurate separation of water and fat. Fortunately, all existing parallel imaging reconstruction techniques are designed to produce the correct magnitude *and* phase in the reconstructed image, so long as accurate coils sensitivity calibration data are available.

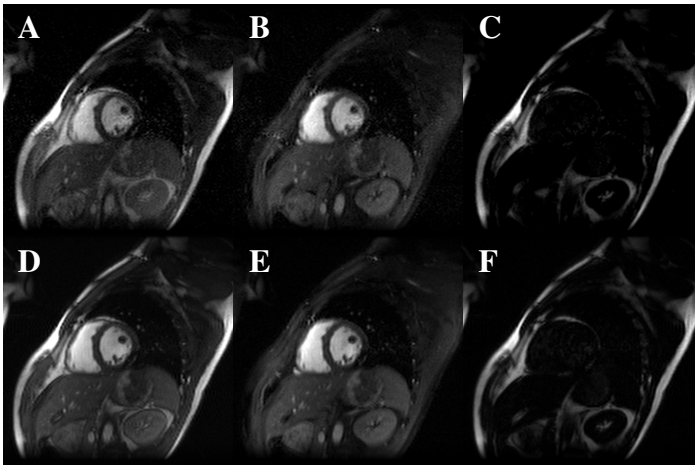
Methods: Image acquisition was performed at 1.5T (Signa CV/i, GEMS, Milwaukee, WI) with a retrospectively ECG-gated CINE SSFP sequence that acquires sequential sets of CINE images at 3 different echo times. One heartbeat was discarded prior to acquisition of each echo time increment to ensure that the magnetization was in steady-state, and 20 CINE phases were retrospectively reconstructed. Automated shimming routines were used for all imaging, and a four-element phased array torso coil was used. Imaging parameters included: TR≈5ms; TE≈0.9, 1.8, 2.7ms; α=50°, BW=±125kHz; FOV=32cm; slice=8mm; N_x=256 (partial echo); views per segment (N_{seg})= 16; temporal resolution=60-80ms. A first data set that was fully sampled in the phase encoding direction (FOV=32cm, N_y=128) was acquired in one breath-hold (27 heartbeats). An under-sampled data set (FOV=16cm, N_y=64) was acquired in a separate breath-hold (15 heartbeats).

After 2D-Fourier transform, the multi-coil source images were reconstructed into combined full FOV images with a hybrid generalized encoding matrix parallel imaging reconstruction (6). Separate water and fat images were calculated using the iterative least-squares water-fat decomposition method (3), and the process was repeated for all CINE phases and all slices. All processing was performed off-line with programs written in Matlab 6.0 (Mathworks, Natick, MA).

Results: Fig. 1 shows source (a), water (b) and fat (c) images (one of twenty phases) reconstructed from under-sampled data acquired in a normal volunteer. Images reconstructed at the same cardiac phase from fully sampled data are shown in Fig. 1d-f for comparison. Source images reconstructed from under-sampled data had minimal artifact, and calculated water and fat images were of diagnostic quality, comparable to those obtained from fully sampled data sets.

Discussion: This preliminary study demonstrates the feasibility of combining parallel imaging with cardiac "Dixon" water-fat separation. The minimum time needed for Dixon water-fat decomposition is increased three-fold over a comparable acquisition with no water-fat separation. Reconstruction of under-sampled data sets with parallel imaging, however, reduces this minimum acquisition time, in this case by a factor of nearly two. The Dixon water-fat separation is a relatively efficient SNR method, with effective signal averaging close to three (3), so that losses in SNR from the parallel reconstruction are largely offset by the gains from the Dixon reconstruction method. For these reasons, the two methods are highly complementary. Further work will be needed to clarify how to quantify SNR in the water and fat images, given that the data has been passed through the parallel imaging-Dixon reconstruction combination.

Reconstruction of the under-sampled data required the use of a calibration scan that was obtained in a separate breath-hold. However, there are a number of ways in which the acquisition of low-resolution coil calibration data can be embedded into the acquisition of under-sampled data without a large time penalty, such as variable *k*-space sampling directly into the pulse sequence acquisition to provide "self-calibrating" data sets (7). This is performed through acquisition of additional lines of k-space acquired at low spatial frequencies. In addition, acquisition with phased array coils with a larger number of elements (eg. 8) should permit acceleration factors such as 3 or higher, which would reduce total scan time to the same as a comparable conventional SSFP CINE acquisition.



Conclusion: We have demonstrated the feasibility of combining parallel imaging with "Dixon" water-fat separation for cardiac SSFP CINE imaging applications. Parallel imaging reduces the long minimum acquisition time needed for water-fat separation, while the high SNR efficiency of the "Dixon" decomposition offsets losses in SNR from the parallel imaging reconstruction.

Fig 1: Short axis SSFP source (a), water (b) and fat (c) images reconstructed from under-sampled data with an acceleration factor of two. Source (d), water (e) and fat (f) images reconstructed from fully sampled data are shown for comparison.

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