Efficient Parallel MRI with 3D Radials using Accelerated PARS Reconstruction

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Introduction: The variable sampling density of 2D and 3D radial trajectories has proven useful for robust imaging in the presence of motion, accelerated scanning through undersampling, and time-resolved imaging. Parallel MRI (pMRI) offers the opportunity to further accelerate radial imaging and improve temporal resolution. Despite recent advances in the efficiency of the iterative SENSE procedure [1,2], pMRI with 3D non-Cartesian trajectories is still computationally challenging for time-resolved studies. Different approximation techniques based on the *k*-space locality principle were proposed for the efficient handling of non-Cartesian trajectories [3,4]. The PARS technique relies on multiple inversions of small matrices constructed using a limited number of samples inside a small radius. PARS creates a solution to the pMRI problem by making direct matrix inversion tractable. However, the computational requirements may be high for 3D imaging. Recently, efficient PARS modifications for non-Cartesian trajectories were proposed [5,6]. The reconstruction acceleration proposed in [6] is achieved by approximating reconstruction coefficients from several directly evaluated reference sets of coefficients distributed in both the angular and radial directions. The approximation is made by means of inexpensive interpolation. Significant reconstruction accelerations (two orders of magnitude) were demonstrated for 2D radials. In this work, we extend the technique to 3D radial imaging for comprehensive imaging of the entire torso.

Materials and Methods: Our approach used synthesized additional projections using low-resolution sensitivity maps estimated from the oversampled *k*-space center in 3D radial imaging. Each point in a given coil dataset was synthesized using a set of neighboring points from acquired radials. The local neighborhood is characterized by the number of participating projections in the azimuthal dimension (δ_ϕ) and the number of points along the radial dimension (δ_r). The multicoil data from the local neighborhood are weighted with precalculated coefficients and combined to create synthesized projections. In our approach, we calculated coefficients only for a few *reference* points distributed in both the radial and azimuthal dimensions providing a reduction of the total matrix inversions by a factor of a_r along the radial direction, and by a factor of a_ϕ along the azimuthal direction. Correspondingly, the total number of matrix inversions is reduced by $a_r a_\phi$. The coefficients for the reference points were directly calculated using the PARS technique, while those for the rest of the points to be synthesized were approximated using bilinear interpolation between the reference coefficient sets as described in Ref. [6]. The data were then regridded onto a Cartesian grid, followed by an inverse 3D FFT to obtain the final image volumes.

The data were collected on a GE 1.5T Twin Speed SIGNA system using a Vastly undersampled Isotropic PRojection (VIPR) sequence [7] designed to generate SSFP contrast. A 40 cm spherical FOV centered over the abdomen was imaged over 52 s with 26,000 projections, each of which sampled 256 readout points during a 2 ms TR. A four element torso array coil was utilized. Even projections were discarded from the dataset to produce reduced data (R=2) which could have been acquired in 26 s. The low-resolution volumes (16x16x16) from the *k*-space center were used to generate *in vivo* sensitivities. Truncated SVD was applied for regularized PARS matrix inversion, with the threshold being chosen as 0.0001 of the maximum singular value. The rest of the parameters for reconstruction were chosen as follows: δ_r=5, δ_ϕ=2, a_r=42, a_ϕ=10. The method was implemented in MATLAB (synthesis of projections) and in C (regridding).

Results: Total reduction of the number of matrix inversions with respect to the full PARS reconstruction of the missing projections was approximately 400. Figure 1 shows images from the reduced (13000 projections), accelerated PARS reconstructed (26000 projections), and fully sampled datasets (26000 projections). A significant reduction in streak artifacts and the mottled appearance of the reduced dataset (a,d) is achieved using the accelerated PARS method. The expected reduction in SNR for accelerated PARS relative to the fully sampled dataset (c,f) is also present. The time to calculate the reference coefficients was about 2 minutes. The other procedures such as linear interpolation with data synthesis and regridding took 9 and 4 minutes, correspondingly.

Discussion: In this work, we have demonstrated that PARS pMRI applied with 3D trajectories exhibits significant reduction in computation time. The achieved acceleration factor transforms a very difficult breath-hold into a reasonable 26 s scan. Efficiency comes from reconstruction acceleration provided by the approximated calculation of coefficients. Using a larger number of arrays and designing optimized trajectories for the given type of arrays may further improve image quality and boost data acquisition speed. These research directions are currently pursued in our lab. Bilinear interpolation was used due to the assumption that only adjacent azimuthal projections close in time to each other should be used for reconstruction. Trilinear interpolation in two angular directions may be used to provide an additional factor of reconstruction acceleration. We expect a significant reduction in reconstruction time when porting the method to C and implementing the *k*-space based PARS matrix construction [5,6]. Additional reconstruction acceleration may be achieved by parallelizing the calculations of coefficients and avoiding reconstructing missing projections in oversampled areas such as the *k*-space center for radials.

Conclusions: An accelerated PARS pMRI algorithm to synthesize *k*-space data has reduced computation time by a factor of 400 in a 3D non-Cartesian acquisition. While an acceleration of 2 allows entire torso imaging in a reasonable breath-hold of 26 s, further acceleration is likely with more than 4 coil elements.

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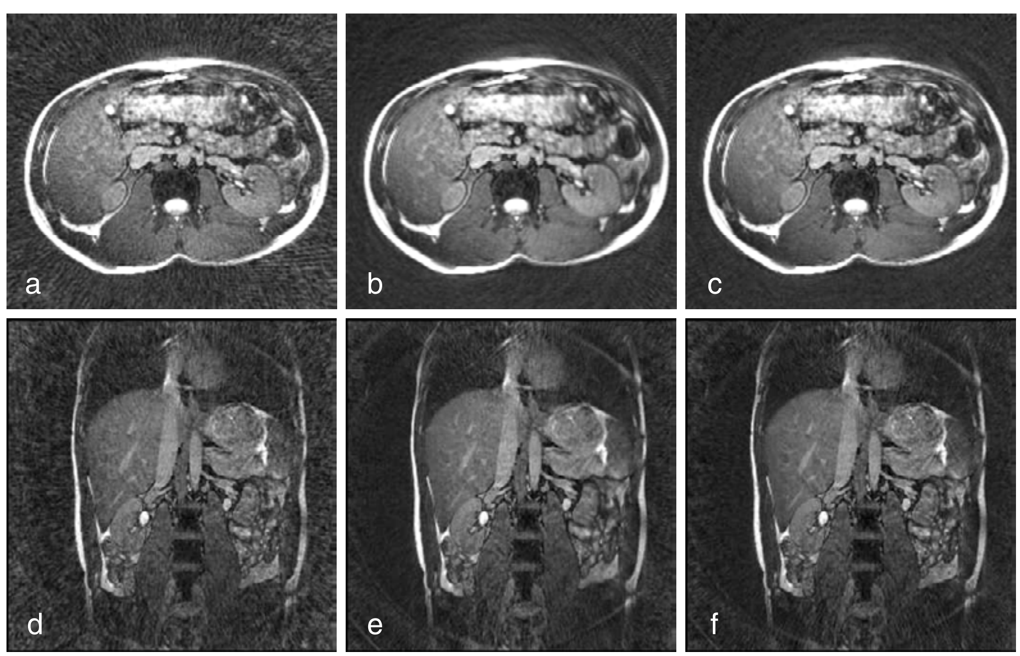

Figure 1. 3D VIPR acquired reduced axial **a)** and coronal **d)** images reconstructed using the accelerated PARS technique **b)** and **e)**, compared with the fully sampled data **c)** and **f)**, respectively.