A Comparison of Reconstruction Techniques for Non-Uniformly Sampled 3D Parallel Imaging

Z. Xiao[1,2], W. S. Hoge[2], R. V. Mulkern[2,3], G. Hu[1], and W. E. Kyriakos[2,3]

[1]Biomedical Engineering, Tsinghua University, Beijing, China, People's Republic of, [2]Radiology, Brigham and Women's Hospital, Boston, MA, United States,

[3]Radiology, Children's Hospital, Boston, MA, United States

Introduction High image acceleration rates can be achieved in 3D parallel imaging via reduced phase encoding steps along both phase-encode directions. Previously, reconstructions using of 2D-SENSE (1) and 2D-GRAPPA (2) were reported. The appearance of artifacts and effective image resolution in reconstructed parallel MR images is directly dependent on the sub-sampling pattern employed. In this work, we explore a specific non-uniform sampling scheme for 3D imaging on a rectilinear grid. We show that high-quality images can be reconstructed by 2D-SPACE RIP and 2D-GRAPPA-Operator. To evaluate the proposed sampling method and reconstruction schemes, results from a phantom study and in-vivo 3D human data are shown. Overall, fewer artifacts can be seen in the 2D-SPACE RIP reconstructions.

Theory The dual-exponential character of *k*-space energy in 2D imaging can be approximated by an inverse exponential form as $Z_{2d}(k_y)=\alpha e^{(-\beta|k_y|)}$. Here, α represents the maximum value of the energy distribution, i.e. the value at $k_y = 0$, and β controls the decay of the exponential. This can be extended to a two-dimensional exponential function in 3D imaging as $Z_{3d}(k_y, k_z)=\alpha e^{(-\beta_y|k_y|-\beta_z|k_z|)}$. This sampling scheme is accompanied by first exponentially weighted sampling in the k_z direction, and then modulating β using a sinusoidal function to sample exponentially in the k_y direction. This two-dimensional pattern allows dense sampling near the origin of k-space---to enable self-referenced coil sensitivity estimation and capture points with higher SNR for reduced visible artifacts---and sparse sampling at the highest sampled frequencies to ensure good resolution. An example is shown in Figure 1 for an acceleration factors of 2.0x and 2.5x along the k_y and k_z directions, respectively, with a central region of 16×16 points sampled at Nuquist-rate at the low frequency of *k*-space (PE1=192, PE2=160). This box of U×V sample points at the low frequency of *k*-space is used for coil sensitivity estimation in 2D-SPACE RIP and for Auto-Calibration Signal (ACS) data in 2D-GRAPPA-Operator. This variable density scheme provides auto-calibrated reconstructions at higher total acceleration-rates than previously reported using SENSE (3).

To reconstruct an image by the 2D-SPACE RIP approach (4), one can form the linear system equation $s=P\bullet\rho$, where 's' denotes MR signal received, 'ρ' represents a plane in the volume of the FOV at position *x* along the frequency encoded direction and 'P' depends on the coil sensitivity estimates and phase-encodes employed (5). Following the extraction of coil sensitivity by filtering the Nyquist-rate sampled low-frequency *k*-space data, we performed reconstruction using a regularized Conjugate Gradient Least-Squares (CGLS) iterative method.

The 2D-GRAPPA-Operator (2) reconstruction method is an extension of 1D-GRAPPA to 3D imaging. It performs GRAPPA reconstruction along two phase encoding directions sequentially and results in improved image quality over 2D-GRAPPA.

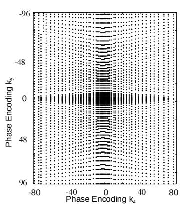

Figure 1. Proposed exponentially weighted sampling pattern on a rectiliniear grid for 3D parallel imaging.

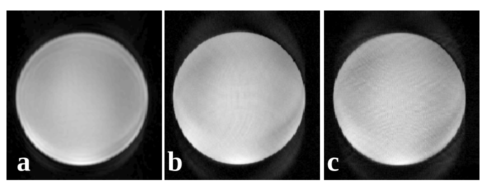

Figure 2.
Image quality comparison between (a) reference image, (b) 2D-SPACERIP reconstructions for a reduction factor $R= R_y\times R_z = 2\times2.5$ and (c) 2D-GRAPPA-Operator reconstruction with the same acceleration rate.

Methods Full FOV 3D doped uniform water phantom and T2-weighted 3D Fast Recovery Fast Spin-Echo sequence (3DFRFSE) whole brain acquisitions, both with and without proposed non-uniform sub-sampling were performed on the GE Signa EXCITE 3.0T scanner equipped with the standard 8 channel head array coil (GE Medical Systems, Milwaukee, WI, USA). Acquisition parameters were: TR/TE = 2600/200 ms, image size = 256×192×160, FOV = 24.0×24.0×20.8 cm^3, receiver bandwidth = 31.25 kHz, echo train length (ETL) = 48, echo spacing = 7.6ms, number of excitations (NEX) = 1. Both accelerated experiments were performed with reduction factor $R=R_y\times R_z=2\times2.5$, $\beta_y=\beta_z=1.2$, 16×16 total ACS lines.

Results Fig. 2 shows one slice of the reference phantom image along the readout direction and reconstructed image of the accelerated scan: $R=R_y\times R_z=2\times2.5$, $\beta_y=\beta_z=1.2$ and U×V =16×16. As can be seen, the 2D-SPACE RIP reconstruction method produces images with less coherent artifacts and noise amplification than the 2D-GRAPPA-Operator method. Fig. 3 shows in vivo non-accelerated images and accelerated 2D parallel imaging results where data were acquired using the same sampling pattern. It is clear from the figure that the remaining foldover artifacts are better suppressed in the 2D-SPACE RIP image than in the 2D-GRAPPA-Operator reconstructions.

Discussion Non-uniform sampling along one dimension was previously shown to yield improved 2D imaging in comparison to uniform sub-sampling. In this abstract, we demonstrated an extension of our non-uniform sub-sampling strategy to 3D imaging and presented a comparison between 2D-GRAPPA-Operator and 2D-SPACE RIP reconstruction methods. The results showed less artifacts and noise amplification in 2D-SPACE RIP images both in phantom and in vivo, though the difference is less accentuated in vivo. We believe this is due to the fact that GRAPPA is non-optimal in the least-squares sense, which appears to be critical at higher acceleration factors. In contrast, one has greater control to suppress noise with the regularized CGLS algorithm. This combination provides an effective approach to significantly reduce the acquisition time in 3D MR imaging using parallel imaging.

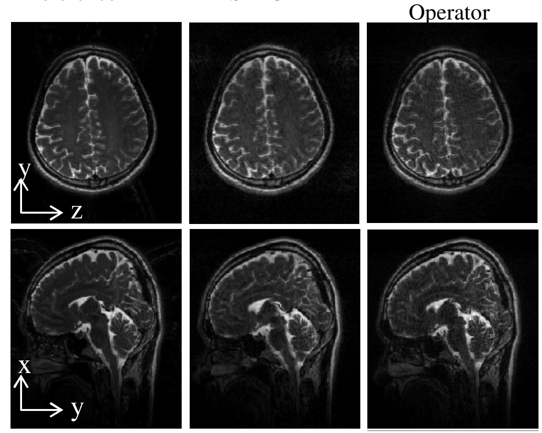

Figure 3. Results from in vivo 3D FSE experiments. Displayed are reference images (left column) and 5x accelerated images reconstructed with 2D-SPACE RIP (middle column) and 2D-GRAPPA-Operator approach (right column).

References:

[1] Weiger M, et al. MAGMA 2002;14(1): 10-19
[2] Blaimer M, et al. MRM 2006; 56(6):1359-1364
[3] Yao et al. AJR 2007;188(2):W199-W201
[4] Hoge WS, et al. Proc. ICASSP 2005;pg 141-144
[5] Hoge WS, et al. CMR 2005;27A(1);17-37

Acknowledgements: This work is supported by National Natural Science Foundation of China (NSFC 30670578)