RF PULSE DESIGN METHODS FOR REDUCTION OF IMAGE ARTIFACTS IN PARALLEL RF EXCITATION: COMPARISON OF 3 TECHNIQUES ON A 3T PARALLEL EXCITATION SYSTEM WITH 8 CHANNELS

A. C. Zelinski[1], L. L. Wald[2,3], K. Setsompop[1], V. Alagappan[3], B. A. Gagoski[1], F. Hebrank[4], U. Fontius[4], F. Schmitt[4], and E. Adalsteinsson[1,2]

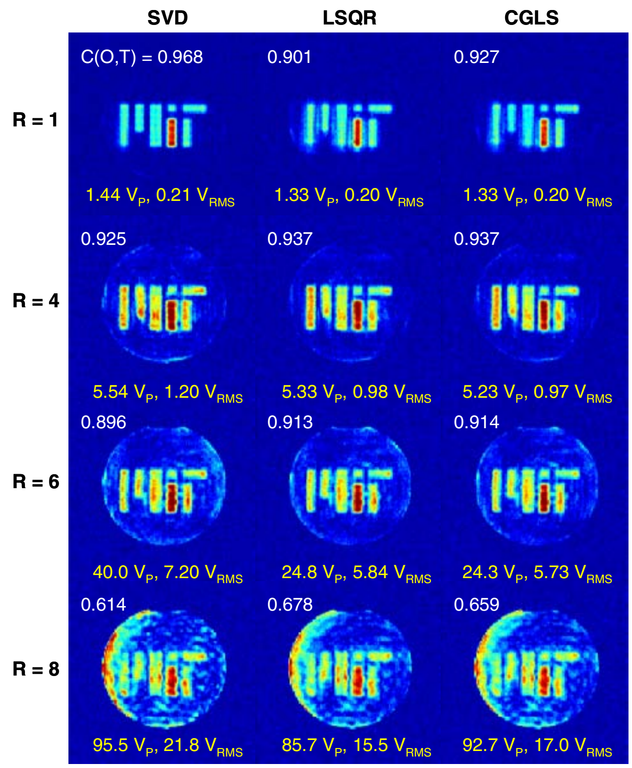
[1]Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, United States, [2]Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology, Cambridge, MA, United States, [3]A. A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Harvard Medical School, Charlestown, MA, United States, [4]Siemens Medical Solutions, Erlangen, Germany

INTRODUCTION: Parallel RF excitation allows one to accelerate the trajectory of spatially-tailored excitation patterns to perform shaped-volume excitation [1] and mitigate B_1-inhomogeneity at high field. We investigate three methods of RF waveform design for such systems, comparing a singular value decomposition (SVD)-based method to Least Squares QR (LSQR) [2] and Conjugate Gradient Least Squares (CGLS) [3]. The latter two algorithms are designed to quickly and accurately solve large linear systems. For a given *k*-space acceleration factor (R = 1, 4, 6, 8), the target excitation pattern (a 2-D logo) and *k*-space trajectory (a 2-D spiral) are kept constant, and the target is excited in a phantom using an 8-channel parallel TX array on a 3T Siemens Magnetom TRIO scanner, a TIM system [4]. Voltage characteristics of the waveforms produced by each method are compared and correlation coefficients between the target and each resulting excitation image are analyzed.

METHODS & RESULTS: **Waveform design**. The RF waveforms and resulting excitation, after linearization via Grissom's formulation [5], are related as follows: $m(r)=i\gamma\sum_{p=1}^{P} S_p(r)\int_0^T B_{1,p}(t)\exp(ir\cdot k(t))dt$, where r is a spatial variable, $m(r)$ the approximate transverse magnetization, γ the gyromagnetic ratio, $S_p(r)$ the sensitivity profile of the p-th coil, $B_{1,p}(t)$ the RF along the p-th coil, and T the duration of each RF. $k(t)$ is the excitation *k*-space trajectory, a function of the gradient. Discretizing this equation yields the linear system **m=Ab**, where **m** is an Mx1 vector of discretized elements of $m(r)$, **b** is a voltage vector of the sampled $B_{1,p}(t)$ and **A** is an MxN matrix incorporating $S_p(r)$ and $k(t)$.

Solving m=Ab. One way of approximately solving for **b** is to use the truncated pseudo-inverse of **A**, generated via an SVD [6]. We solve for **b** using this SVD-based method and also use two other algorithms: LSQR and CGLS. Specifically, for a fixed value of R, each algorithm is used to generate a set of RF waveforms. The design parameters and RF peak voltage of each method are tuned such that the noise floor across all images is the same and the flip angles of the resulting excitations are approximately equal (within 1-5% for fixed $R > 1$). LSQR is similar to the regularized pulse design method introduced by Yip [7] and subsequently extended to emulated parallel systems by Grissom [8].

Figure 1: Resulting Excitation Images



Correlation coefficients. To compare the excitation images generated by each algorithm, the correlation coefficient, C, between each observed excitation, **O**, and the target image, **T**, is computed and displayed above each of the observed excitation images in **Figure 1**. $C(\mathbf{O},\mathbf{T})=\sigma_{\mathbf{O}}^{-1}\sigma_{\mathbf{T}}^{-1}\,\mathrm{Cov}(\mathbf{O},\mathbf{T})$, where Cov(**O**, **T**) is the covariance between the images calculated over the region where at least one coil profile is active and $\sigma_{\mathbf{O}}$, $\sigma_{\mathbf{T}}$ are the variances of each respective image in the same region. C quantifies the similarity between **O** and **T**; the closer it is to unity, the more similar **O** is to **T**. For fixed $R > 1$, LSQR and CGLS images have higher C values than those from the SVD-based method, implying that LSQR and CGLS produce excitations with fewer artifacts that better resemble the target pattern.

Peak & RMS Voltages. The peak voltage, V_P, and root-mean-square (RMS) voltage, V_{RMS}, of each **b** vector appear below each image in **Figure 1**. For fixed R, LSQR and CGLS yield lower V_P and V_{RMS} than the SVD-based method, which implies lower specific absorption rates (SAR), in line with Grissom et al.'s observations when designing waveforms for an emulated parallel system [8]. Further, V_P and V_{RMS} grow rapidly as a function of R, which may pose constraints on *in vivo* applications. Such rapid growth underscores the challenge of $R >> 1$ designs.

CONCLUSION: By solving a linear system of equations with algorithms tuned for numerical stability, it is possible to achieve parallel excitation of the *same* target pattern with less artifacts and lower peak and RMS voltages than with truncated SVD inversion, as demonstrated via experiments conducted on a 3T Siemens Magnetom TRIO, a TIM system, equipped with an 8-channel TX array.

ACKNOWLEDGEMENTS & REFERENCES: Siemens Medical Solutions, NIH P41RR14075, US DoD NDSEG Fellowship, R. J. Shillman Career Development Award.
[1] Pauly et al. A *k*-space analysis of small-tip angle excitation. *JMR*. 1989;81:43-56. **[2]** Paige CC, Saunders MA. LSQR: An algorithm for sparse linear equations and sparse least squares. *ACM Trans. on Math. Software*, 1982;8(1):43-71. **[3]** Paige CC, Saunders MA. CGLS: CG method for Ax=b and Least Squares. Online. stanford.edu/group/SOL/. **[4]** Setsompop et al. Parallel RF Transmission with 8 Channels at 3T. *MRM*. 2006;56(5):1163-1171. **[5]** Grissom et al. A new method for the design of RF pulses in Transmit SENSE. *2nd Int'l Workshop on Parallel Imaging*, pg. 95, 2004. **[6]** Golub GH, Van Loan CF. *Matrix Computations*. JHU Press, 1983. [7] Yip et al. Iterative RF pulse design for multidimensional, small-tip angle selective excitation. *MRM*. 2005;54(4):908-917. **[8]** Grissom et al. Spatial Domain Method for the Design of RF Pulses in Multicoil Parallel Excitation. *MRM*. 2006;56(3):620-629.