Joint SENSE Reconstruction for Faster Multi-Contrast Wave Encoding

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Synopsis

We introduce Joint SENSE acquisition/reconstruction to provide higher acceleration in multi-contrast acquisitions with improved image quality. We employ a complementary sampling strategy across the contrast by shifting the k-space sampling patterns across the contrasts, which induces phase ramps in image space. By harnessing these ramps as additional coil sensitivity variations, we improve reconstruction error and g-factor performance by >2x compared to standard SENSE reconstruction. Further, we combine Joint SENSE with Wave encoding to exploit 4-dimensional sensitivity encoding, 3D across space + 1D across contrasts, to provide rapid multi-contrast acquisition with high quality.

Introduction

Multi-echo acquisitions are ubiquitous in clinical and research applications, with applications in T2/T2* parameter mapping, water-fat separation [1], BOLD sensitivity enhancement [2,3] and B0 field estimation [4]. The image information in these echoes feature substantial similarities, which can be leveraged using model-based reconstruction [5], joint-sparse and/or low-rank regularization [6,7].

In this work, we propose Joint SENSE, a complementary approach that exploits similarities between contrasts at the sensitivity encoding level. To this end, we shift the k-space sampling patterns of each echo, which creates phase ramps in image space. We then solve for each individual contrast using k-space data from all echoes, using new and additional coil sensitivities that include the incurred phase ramps. These help synthesize higher order Fourier harmonics, thereby substantially improving pRx capability. We demonstrate the application of joint reconstruction in Wave encoding [8], which now exploits 4-dimensional sensitivity encoding: 3D space + 1D contrast dimension.

Data / code: LINK

Theory

As shown in [Fig1, left], we incur k-space shifts between echoes during the multi-contrast acquisition. Due to Fourier shift theorem, shifted sampling creates a phase ramp in image ρ:

$$shift(F \cdot \rho) = F \cdot (\rho e^{j \cdot ramp})$$

where F denotes Fourier Transform and $e^{j \cdot ramp}$ represents the phase ramp. We employ these ramps for extra spatial encoding. By stacking data from all contrasts in the coil axis, we create additional channels and obtain the Joint SENSE forward model [Fig1, right]:

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \rho_1 = \begin{bmatrix} C \cdot \rho_1 \\ C \cdot \rho_2 e^{j \cdot ramp} \end{bmatrix}$$

Here ρ1 and ρ2 are images with different contrasts, and ρ2 has been shifted in k-space to incur $e^{j \cdot ramp}$. C are the actual coil sensitivities (as in conventional SENSE [9]) and C1 and C2 are the unknown sensitivities that will be employed in Joint SENSE.

Sensitivities consistent with the forward model are C1=C and $C2=C \cdot e^{j \cdot ramp} \cdot \rho2/\rho1$. This indicates that the incurred phase ramps are transferred to the additional coil sensitivities C2, along with an undesired contrast-dependent term ρ2/ρ1. To mitigate its effect, we downweight the contribution from other contrasts with λ to obtain the final Joint SENSE model:

$$\begin{bmatrix} F_\Omega C_1 \\ \sqrt{\lambda} \cdot F_\Omega C_2 \end{bmatrix} \rho_1 = \begin{bmatrix} kspace_1 \\ \sqrt{\lambda} \cdot kspace_2 \end{bmatrix}$$

where F_Ω is sub-sampled Fourier transform and $kspace_i$ are the acquired data from contrast i. We iteratively solve for ρ1 using LSQR.

Data Acquisition and Reconstruction

Data acquisitions were performed at 3T. Figs 2&3 employed conventional readout (without Wave) and 16 SVD compressed coils [10,11]. We explored Wave encoding in Fig4 with 24 SVD coils. $\lambda=5 \cdot 10^{-3}$ was used in all Joint SENSE/Wave reconstructions. Joint sensitivities C_i were estimated automatically using ESPIRiT [12,13] after concatenating all echoes in the coil axis. G-factors were computed using 300 Monte-Carlo iterations [14].

Multi-Echo MPRAGE [15,16] [Fig2]: 1mm isotropic resolution, matrix=256x240x192, TEs={1.7, 3.6, 5.4, 7.3} ms, TR/TI=2500/1100 ms, BW=650 Hz/pixel. A slice along readout axis was undersampled by R=5x3-fold. K-space shifts for each echo in Joint SENSE were (Δky,Δkz)=(0,0); (1,1); (2,2); (3,3).

Multi-Echo Spin-Echo [Fig3]: 0.9mm in-plane resolution, matrix=256x216, TEs={30,50,60,75,90} ms, TR=800 ms, BW=130 Hz/pixel, R=5-fold acceleration. For Joint SENSE, the five echoes were shifted by Δky={0,1,2,3,4} samples.

Multi-Echo Wave MPRAGE [Fig4]: Using the same dataset in Fig2, multi-echo Wave was simulated using 3 sinusoidal cycles, Slewmax=180mT/m/s, Gradientmax=14.6mT/m. Joint SENSE/Wave reconstructions were performed with Δky={0,1,2,3} shifts at R=4x3 acceleration.

Results

[Fig2]: Joint SENSE improved RMSE by >2-fold, and successfully mitigated noise amplification with average g-factor G_{avg}=1 compared to G_{avg}=2.8 in SENSE. Such improvement was possible thanks to additional sensitivity encoding and data averaging across echoes.

[Fig3]: Joint SENSE alleviated structured aliasing artifacts and noise amplification present in SENSE, with >2x reduction in RMSE and >4x improvement in G_{avg}.

[Fig4]: Joint SENSE partially mitigated noise and artifacts present in SENSE reconstruction, with 1.4x reduction in RMSE. Combining Joint reconstruction and Wave encoding in Joint Wave provided >2x error reduction with further quality improvement.

Discussion and Conclusion

Joint SENSE acquisition/reconstruction provides >2x improvement in RMSE and g-factor compared to standard SENSE. It can further be enhanced with low-rank and/or joint-sparse priors, and is flexibly extended to include Wave encoding. Joint Wave is particularly helpful in high-bandwidth ME-MPRAGE acquisitions, where the readout period is too short to play a large Wave corkscrew, limiting the benefit from Wave encoding alone.

A drawback is the contrast weighting in the extra coil sensitivities, which was mitigated by downweighting their contribution. This complicates Joint SENSE reconstruction of ME-GRE data with large ΔTE, where large differences between phase of the echoes counteract the effect of the added phase ramps. Phase navigator/ACS information could help address this drawback.

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Figures

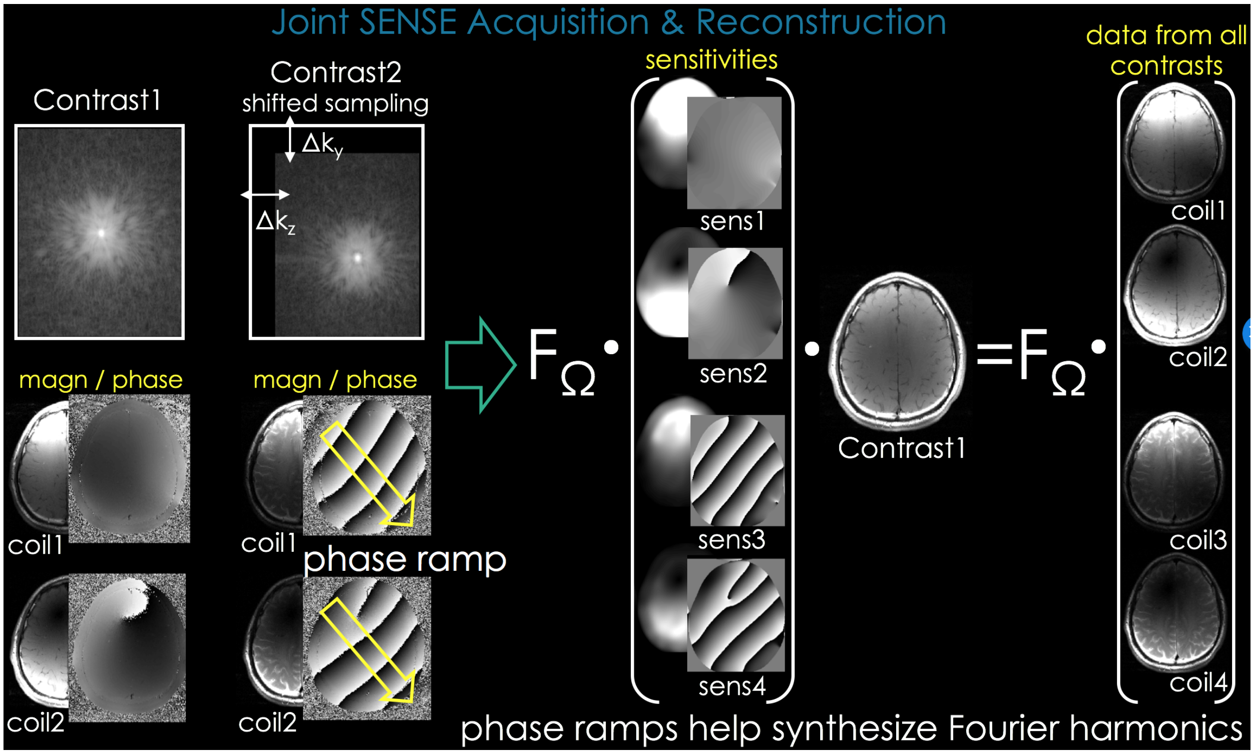

Fig1. *In multi-contrast acquisition, we perform shifted sampling in k-space across different echoes, which incurs phase ramps in image space. During Joint SENSE reconstruction, coil data from all contrasts and all channels are stacked together, so that all images contribute to the reconstruction of a particular contrast. Concatenating the coil data from all images allow us to automatically transfer the incurred phase ramps to the ESPIRiT sensitivity maps. Added phase variations thus provide extra spatial encoding, and substantially improve pRx capability.*

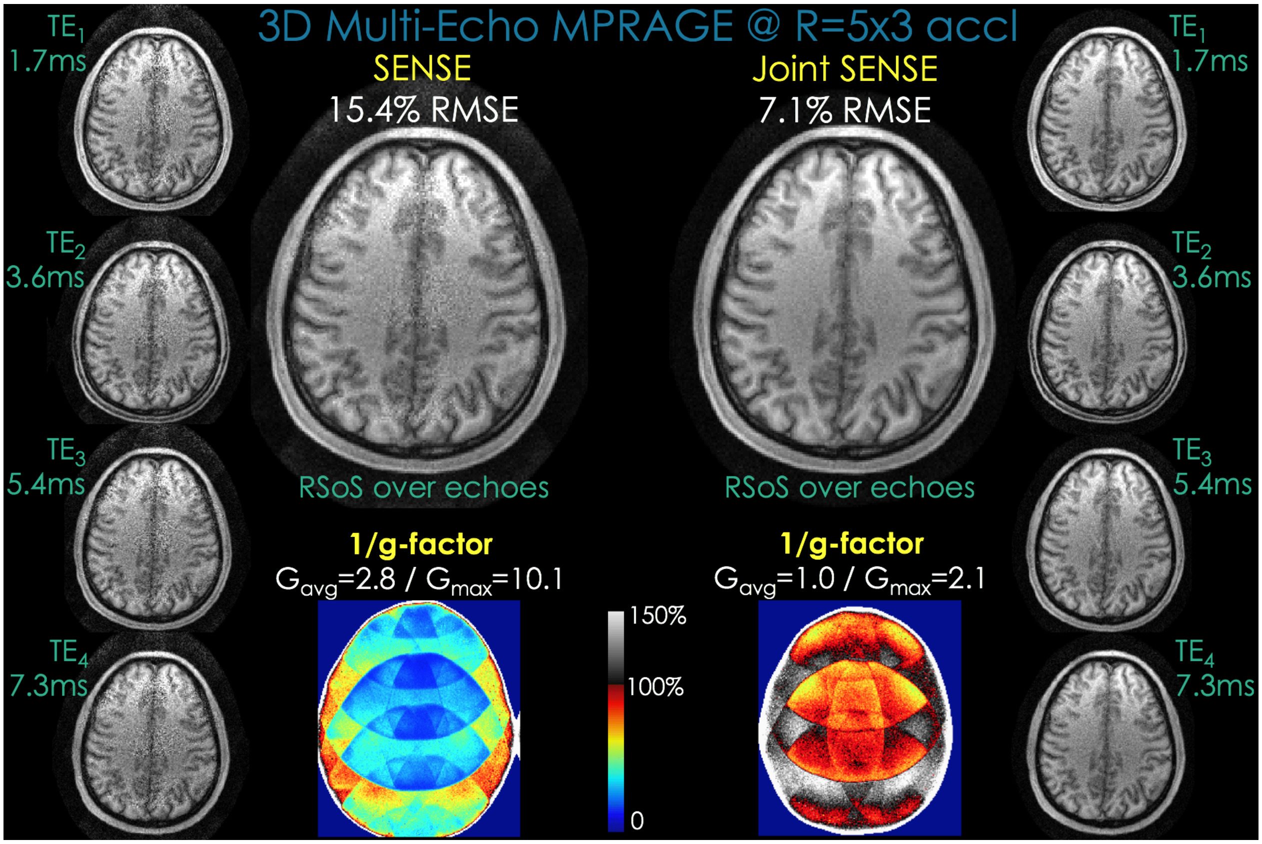

Fig2. ***[Left]*** *Standard SENSE reconstruction for multi-echo MPRAGE acquisition at R=15-fold acceleration. Both individual echoes and the RSoS combined image suffer from severe noise amplification and artifacts, as quantified by the g-factor analysis and RMSE (G_{avg}=2.8, 15.4% error).* ***[Right]*** *Joint SENSE provides >2x improvement in g-factor and RMSE, with substantially improved image quality. We note that despite achieving G_{avg}=1.0 thanks to noise averaging across echoes, the intrinsic sqrt(R) penalty on SNR due to undersampling still impacts the reconstruction.*

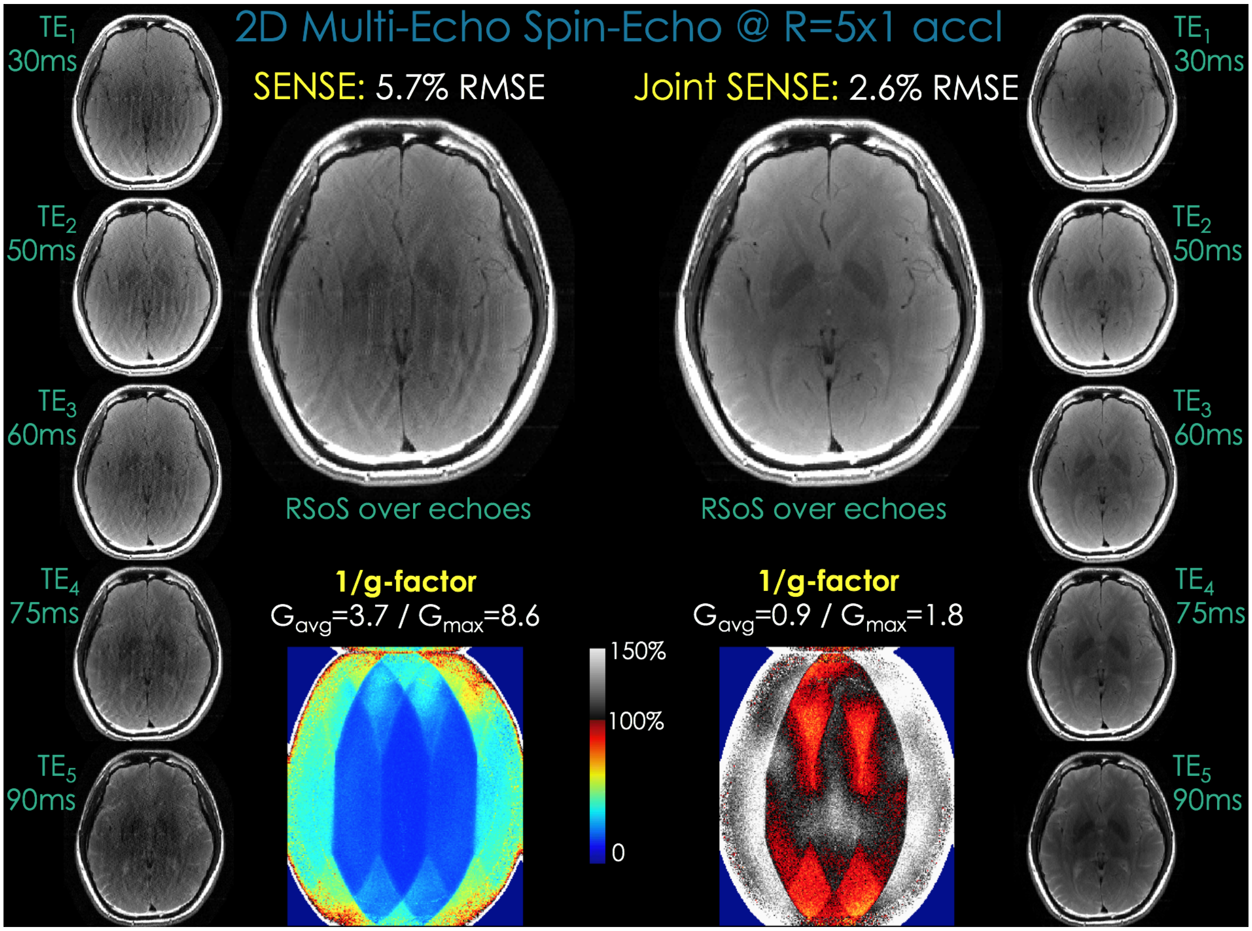

Fig3. [Left] Individual and RSoS combined echoes in 5-fold accelerated 2D multi-echo SE acquisition using standard SENSE reconstruction. Such high acceleration in the right-left direction with tight FOV resulted in structured aliasing artifacts and high g-factor noise amplification. [Right] Joint SENSE reconstruction provided >2x improvement in both RMSE and g-factor performance, yielding high SNR images with low artifact levels.

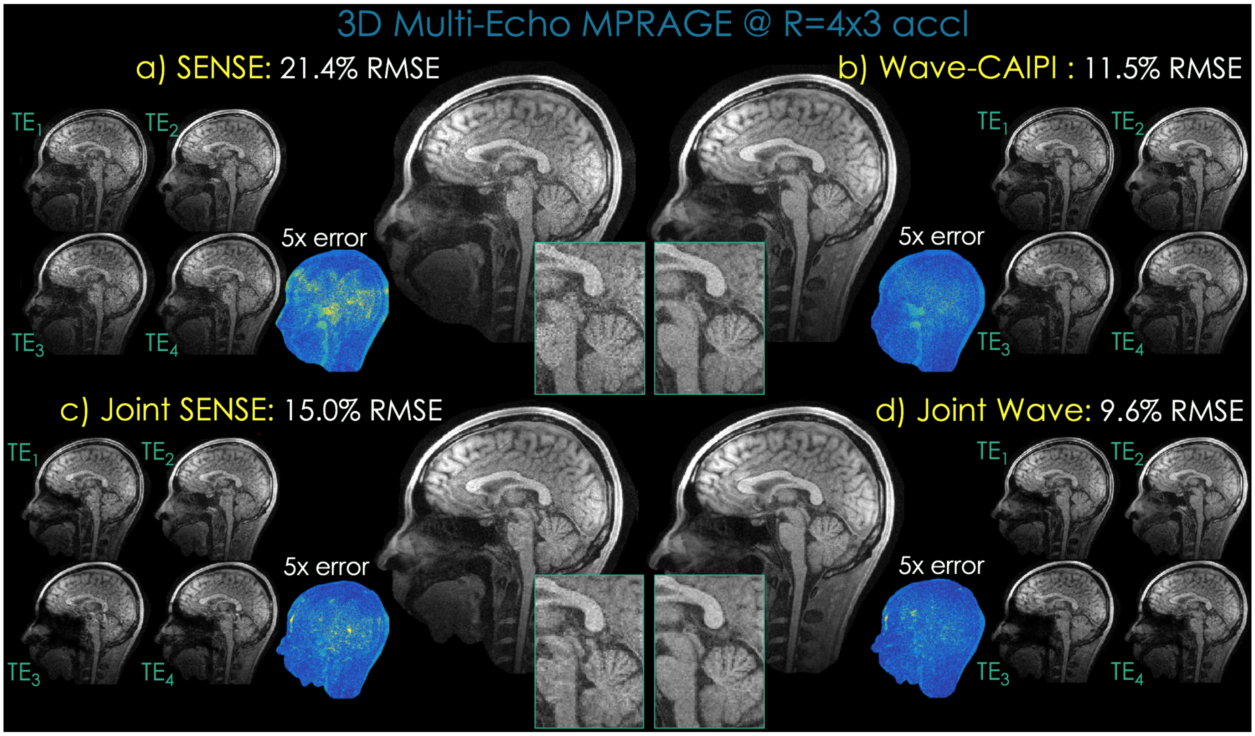

Fig4.* *a) *Multi-echo MPRAGE with standard SENSE reconstruction at R=4x3 (As in Fig2, R_y and R_z are along anterior-posterior and left-right directions, with readout lying along head-foot). SENSE suffered large RMSE, in part due to low receiver sensitivity and low signal in the nasal cavity/mouth regions in this sagittal view.* ***b)*** *Wave-CAIPI spreads the aliasing in 3D to improve RMSE and SNR retention.* ***c)*** *Joint SENSE utilizes the additional sensitivity encoding through shifted sampling, yet yields worse performance than Wave encoding alone.* ***d)*** *Combination of Wave and Joint SENSE is powerful, providing >2x RMSE improvement and cleaner reconstruction.*