NEATR-SMS for highly accelerated multi-shot EPI

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Purpose: Multi-shot EPI (msEPI) allows high-resolution imaging with reduced distortion, but combining shots is prohibitively difficult because of shot-to-shot phase variations. These variations can be mitigated using navigators, albeit at the cost of imaging efficiency and potential artifacts. Navigator-free approaches employ parallel imaging (PI) to reconstruct each shot, from which phase variations are estimated [1,2]. This imposes a limit on the distortion reduction since PI breaks down beyond $R_{\text{inplane}}>4$ acceleration. MUSSELS [3] is a new low-rank constrained PI approach which improves the ability to accelerate in msEPI, but requires a large number of shots ($R_{\text{inplane}}=8$ with 4-shots). Here we propose NEATR-SMS (Network Estimated Artifacts for Tempered Reconstruction-Simultaneous MultiSlice, Fig1) for navigator-free msEPI and achieve 16-fold acceleration using only 3-shots. With this approach, we start with an extended version of MUSSELS that incorporates SMS and use a residual network to minimize the MUSSELS-SMS artifacts at high accelerations. This refined reconstruction allows us to accurately solve for the shot-to-shot phase variations, which are incorporated in a final Joint Virtual Coil (JVC-) SENSE reconstruction. This way NEATR-SMS fully harnesses sensitivity encoding and all the acquired data, while avoiding end-to-end application of ML.

Acquisition: Four volunteers were scanned using spin-and-gradient-echo (SAGE) msEPI [4] with 8-shots at *prospective* $R_{\text{inplane}}=8$ acceleration (FOV=224x224x120 mm^3, 1x1x3 mm^3 resolution, TEs= 26/61/61/130/165 ms, TR=8.3 sec) on a 3T system with a 32-channel head coil. MUSSELS was employed to jointly reconstruct all 8-shots to provide "ground-truth" reference images.

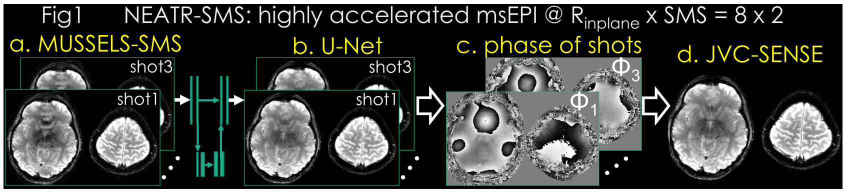
Fig1 NEATR-SMS: highly accelerated msEPI @ R_{inplane} x SMS = 8 x 2

Recon @ R_{inplane}xSMS = 8x2: Out of the 8-shots, 3-shots at Δk_y shifts={0, 3, 6} samples were selected, and groups of two slices (60 mm apart) were collapsed to simulate SMS=2. A new approach was developed to allow MUSSELS to work with SMS reconstruction using the readout-extended FOV concept [5,6]. This represents SMS as undersampling in the k_x axis by concatenating the two slices along the *readout* (Fig1). Inplane and slice acceleration could thus be captured using a single Fourier operator $\mathrm{F_t}$ with k_x-k_y undersampling in shot t to solve $min_{\boldsymbol{x}} \sum_{t=1}^{N_s} \|\mathrm{F_t C} x_t - d_t\|_2^2 + \lambda \|\mathcal{H}(\boldsymbol{x})\|_*$. Here, C are the concatenated receive profiles of the two slices and $\boldsymbol{d_t}$ are the slice-collapsed shot k-space data. The constraint $\|\mathcal{H}(\boldsymbol{x})\|_*$ enforces a low-rank prior on the block-Hankel representation of the multishot data $\boldsymbol{x}$, which is formed by concatenating the images x_t from N_s shots. This solution provided corrupt input for ML (Fig1a).

Residual U-Net (Fig1b): learned a mapping between the 3-shot MUSSELS-SMS and the error relative to the reference images from the 8-shot acquisition. Three volunteers' data were used for training and the fourth subject was reserved for testing. U-Net [7] with 5 levels, ℓ_2 loss, leaky ReLU activation and 64 filters at the highest level was trained on 64x64 patches. Real and imaginary parts of all 3-shots were presented as channels for complex-valued processing. Training set was augmented 16-fold with scaling, flips and rotations.

JVC-SENSE: The refined U-Net magnitude m_{unet} allows us to solve for the phase of t^{th} shot ϕ_t with wavelet (Ψ) regularization [8]: $min_{\phi_t} \left\| \mathrm{F_t C} e^{i\phi_t} m_{unet} - d_t \right\|_2^2 + \alpha \|\Psi \phi_t\|_1$ (Fig1c). Shot phases from the complex U-Net reconstruction were used to initialize this non-convex problem. Once phase variations are estimated, we solve for the magnitude m using data from all shots: $min_m \sum_{t=1}^{N_s} \left\| \begin{bmatrix} \mathrm{F_t C} e^{i\phi_t} \\ \mathrm{F_{-t} C^*} e^{-i\phi_t} \end{bmatrix} m - \begin{bmatrix} d_t \\ {d_{-t}}^* \end{bmatrix} \right\|_2^2 + \beta \cdot \mathrm{TV}(m)$ (Fig1d). Here, virtual coil k-space ${d_{-t}}^*$ and the corresponding conjugate sensitivities $\mathrm{C^*} e^{-i\phi_t}$ ensure that m is real-valued, and $\mathrm{TV}(\cdot)$ represents total variation penalty.

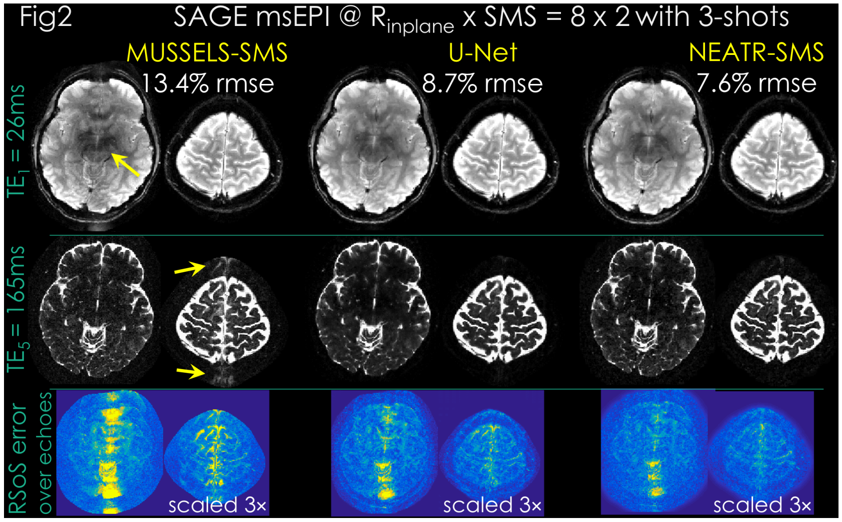
Fig2 SAGE msEPI @ R_{inplane} x SMS = 8 x 2 with 3-shots

Results: (Fig2) shows 2 echoes (out of 5) from a slice group where MUSSELS-SMS yielded 13.4% rmse with ghosting/aliasing artifacts (arrows). U-Net mitigated these (8.7% error), allowing JVC-SENSE to provide clean images (7.6% rmse). 2D-SENSE [9] broke down (43.9% error, not shown) due to 16-fold acceleration. Using the SAGE signal equation yielded T_2 and T_2* maps with whole-brain coverage in 12.5 sec (Fig3).

Conclusion: We introduced MUSSELS-SMS and used it as an input to our residual network, which enabled 16x accelerated msEPI using 3-shots. NEATR-SMS synergistically combined ML with model-based reconstruction, and further improved the quality with a final physics reconstruction to prevent end-to-end application of ML. NEATR-SMS reduced RMSE by 1.8-fold over MUSSELS-SMS to enable a whole-brain, navigator-free, quantitative exam with high geometric fidelity.

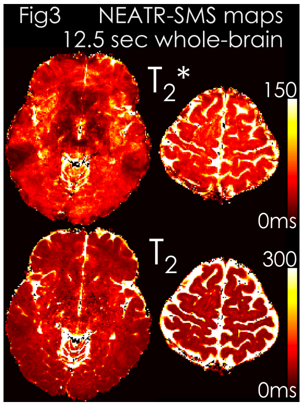
Fig3 NEATR-SMS maps 12.5 sec whole-brain

References: [1] N Chen, NIMG'13; [2] Z Zhang, NIMG'15; [3] M Mani, MRM'17; [4] H Schmiedeskamp, MRM'12; [5] S Moeller, ISMRM'14; [6] P Koopmans, ISMRM'15; [7] O Ronneberger, MICCAI'15; [8] F Ong, MRM'17; [9] K Pruessmann, MRM'99.