VUDU-SAGE: Efficient T_2 and T_2^* Mapping using Joint Reconstruction for Motion-Robust, Distortion-Free, Multi-Shot, Multi-Echo EPI

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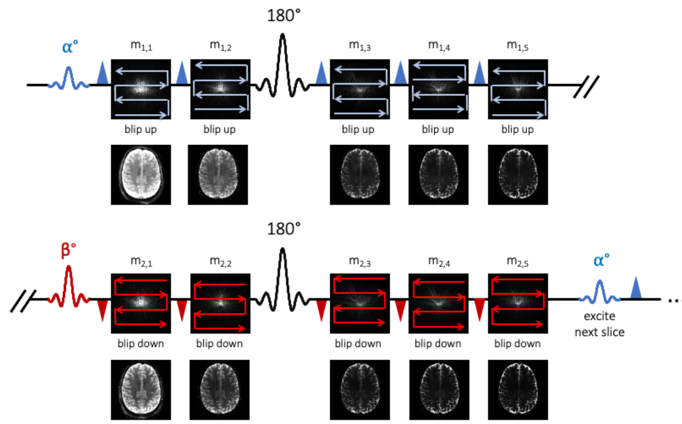

***Figure 1**. The sequence diagram of VUDU-SAGE*

Introduction: Variable flip, blip-up and -down undersampling (VUDU) enables motion-robust, distortion-free multi-shot EPI (ms-EPI). VUDU incorporates blip-up and -down acquisition (BUDA) strategy for distortion correction, fast low angle excitation echo-planar technique (FLEET) for motion-robustness and variable flip angle (VFA) method for maximizing the signal. BUDA employs interleaved blip-up/-down phase encoding and incorporates B_0 forward-modeling into structured low-rank reconstruction to enable distortion-free and navigator-free msEPI. FLEET significantly reduces the acquisition time frame for each slice while maximizing the signal using VFA, e.g. 45° and 90° RF pulses for 2-shot EPI. Spin and gradient echo (SAGE) acquires multiple echoes for each shot and enables T_2 and T_2^* mapping. BUDA-SAGE successfully incorporated the BUDA strategy into the SAGE acquisition, and enabled distortion-free multi-contrast and quantitative imaging. However, standard msEPI ordering requires a time gap of several seconds between multiple shots, which increases the vulnerability to motion. In this abstract, we introduce VUDU-SAGE for efficient T_2 and T_2^* mapping using joint reconstruction of motion-robust, distortion-free, multi-echo msEPI.
Data/Code: https://anonymous.4open.science/r/vudu-sage/

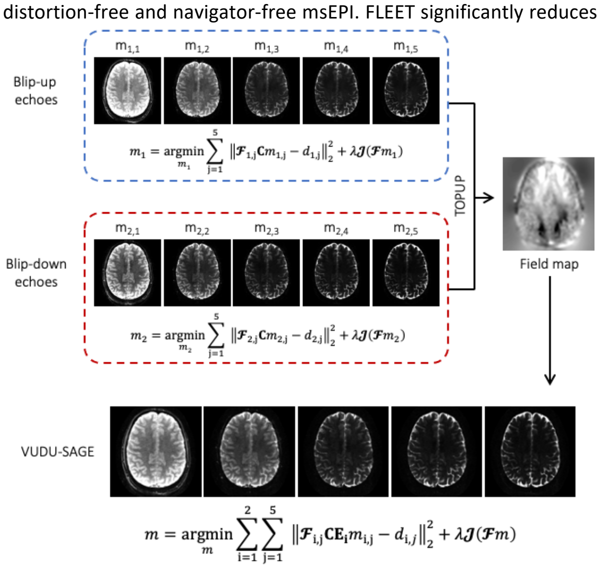

***Figure 2.** VUDU reconstruction pipeline*

Methods: **Figure 1** shows the VUDU-SAGE sequence diagram. VUDU-SAGE employs FLEET-ordering that successively excites a specific slice for motion-robust imaging, while incorporating VFA to maximize the signal. Each excited slice is fully encoded within a short timeframe (~320 msec) before exciting and encoding the next slice. VUDU-SAGE encodes the first-shot and the second-shot signal by a blip-up and -down readouts, respectively. VUDU-SAGE acquires five echoes consisting of two gradient-echo, two mixed, and one spin-echo contrast. Each echo covers different k-space lines to provide complementary information from each echo.
Figure 2 shows the reconstruction pipeline of VUDU-SAGE. First, five echoes are jointly reconstructed for each shot. Low-rank modeling of local k-space neighborhoods (LORAKS) framework was used for the joint reconstruction as the following equation.

$$m_i = \underset{m_i}{\text{argmin}} \sum_{j=1}^{5} \|\mathcal{F}_{i,j} \mathbf{C} m_{i,j} - d_{i,j}\|_2^2 + \lambda \mathcal{J}(\mathcal{F} m_i)$$

where $\mathbf{C}$ are sensitivities, $\mathcal{J}$ is LORAKS regularization, and $i = 1$ stands for blip-up and $i = 2$ for blip-down. $\mathcal{F}_{i,j}$, $m_{i,j}$ and $d_{i,j}$ are the undersampled Fourier transform, fully-sampled image, and acquired k-space data for j^{th}-echo in the i^{th} shot, respectively. Once blip-up and -down echoes were reconstructed, we use them to estimate a field map $\mathbf{E}$, using the TOPUP algorithm. Incorporating B_0 forward-modeling into the joint reconstruction of two-shot, five-echo data (ten images in total), the distortion-free images can be calculated as follows.

$$m = \underset{m}{\text{argmin}} \sum_{i=1}^{2} \sum_{j=1}^{5} \|\mathcal{F}_{i,j} \mathbf{C} \mathbf{E}_i m_{i,j} - d_{i,j}\|_2^2 + \lambda \mathcal{J}(\mathcal{F} m)$$

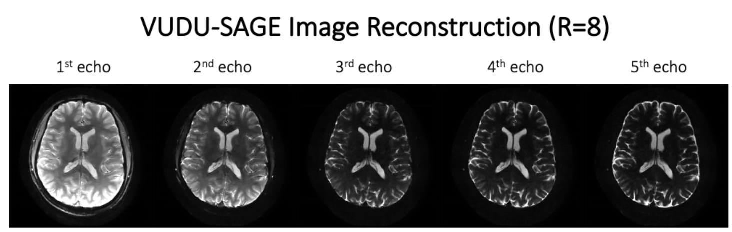

***Figure 3**. The reconstructed distortion-free VUDU-SAGE images*

T_2 and T_2^* maps are obtained through Bloch dictionary matching on the reconstructed echoes.

Experiment: We conducted experiments on a Siemens 3T Prisma scanner equipped with a 32-channel head coil. 2-shot VUDU-SAGE acquisition was used at 8-fold acceleration per echo. The imaging parameters for VUDU-SAGE were voxel size=1x1x4mm^3, partial Fourier factor = 6/8, TE= [18.11, 39.91, 87.56, 109.36, 131.16] msec, TR_{slice}= 150 msec, slice time frame = 320 msec, and total acquisition time = 9 sec, respectively. We applied the VFA RF-pulses at flip angles α=37 and β=-90, to take into account T_1 recovery during the inter-shot gap. The T_2 reference map was obtained using SE acquisitions with TE=[25,50,75,100,125] msec. The T_2^* reference map was obtained using multi-echo gradient-recalled echo (mGRE) acquisition with TE=[4,11,18,25,32,39,46] msec. To further denoise the images, we used the image denoising network after the joint reconstruction.

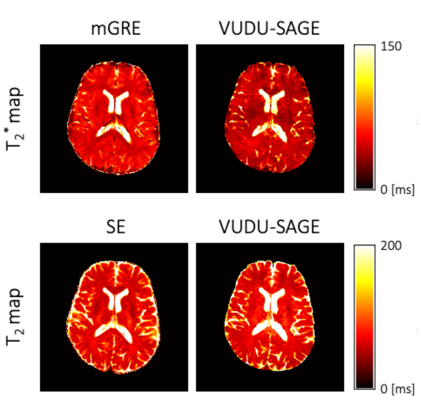

***Figure 4**. The estimated T_2 and T_2^* maps*

Results: **Figure 3** shows the reconstructed distortion-free VUDU-SAGE images. The figure presents the reconstructed motion-robust, distortion-free, high-fidelity five echoes.
Figure 4 shows the references and estimated T_2 and T_2^* maps. The estimated T_2 values were well aligned with the reference. The T_2^* map was slightly underestimated (6.7 msec), compared with the reference.

Discussion & Conclusion: We introduce VUDU-SAGE that allows motion-robust, distortion-free T_2 and T_2^* mapping. In-vivo experiment presents high-fidelity multi-echo images via joint reconstruction and efficient T_2 and T_2^* mapping using 9-second VUDU-SAGE acquisition. Although the T_2^* map was underestimated in the in-vivo experiment, we think including the B_1 field in the signal evolution model will help improve the accuracy of T_2^* mapping. We think VUDU-SAGE will also allow para- and dia-magnetic susceptibility mapping. Incorporating a neural network into joint reconstruction will further improve the distortion-free images and quantitative maps. Employing simultaneous multislice (SMS) imaging will further accelerate the imaging speed and employing gSlider will boost SNR and permit high isotropic resolution, thereby allowing a 20-second whole-brain quantitative MRI at the voxel size of 1x1x1mm^3. We expect that VUDU-SAGE can be extended to fetal, cardiac, and abdominal imaging, where motion is unpredictable and non-rigid.

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